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Aerial Ice Dam Control & Removal

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Abstract

Ice dams can cause serious damage to homes during the wintertime. A multirotor mounted solution was sought to drop salt on these ice dams, allowing backed-up water to flow through and prevent water damage. Two mechanisms were developed and prototyped. The prototypes had rapid interchangeability and a unified static multirotor mount. They were created with rapid prototyping technology for quick assembly and repair, with the majority of parts composed of lightweight laser-cut acrylic and 3D-printed PLA. One mechanism carries and deploys 0.7 kg of standard calcium chloride throw-able ice pucks, while the other carries drops 1.239 kg of granular pet-safe ice melt. They are both controlled manually by the same transmitter/receiver system (tested to a line-of-sight range of over 450m), which is independent of the multirotor flight control system. Both mechanisms perform as intended, and jams are clearable using the transmitter.

Acknowledgements

Firstly, we would like to thank our advisor, Professor Sullivan. He kept us on-task and always cognizant of the practical considerations we may have otherwise overlooked.

Secondly, Joseph St Germain in the Robotics Engineering department proved instrumental in helping with the multirotor aspect of the project. The feasibility of many multirotors and the workings of our electronics (specifically, the transmitter and receiver) went through him first. He also assisted in the procurement of motors and miscellaneous other hardware that we incorporated into the final designs.

Finally, Gregory Tighe, an undergraduate in the Robotics Engineering department, kindly allowed us to survey the S1000+ multirotor that his MQP used as a vehicle. We were able to obtain measurements and a working components list with his assistance.

Authorship

All sections were written and edited jointly by all members.

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Executive Summary

Ice dams present serious problems to homes all throughout the northeastern United States. This common winter occurrence causes snow meltwater to back up on roofs, promoting roof leaks that can cause severe and costly structural or cosmetic damage to homes and personal belongs. Current solutions for addressing ice dams are frequently ineffective, overly expensive, unsafe, or some combination. Therefore, there is a need for a system that can control and remove ice dams in a safe, cost-effective manner.

A multirotor-based solution was sought. Such a strategy allows a trained operator to deploy and control the ice-dam removal system safely from ground level. This would entail deploying both deicing pucks and granular salt onto and around ice dams; these are two of the more effective (and cost-efficient) methods of controlling and removing ice dams. After evaluating a series of preliminary designs, two mechanisms were developed that would fit onto a multirotor one at a time, with the possibility of rapid interchange between them. One mechanism was for carrying and deploying deicing pucks, and one was for carrying and deploying granular salt.

Desired payload capacities for each mechanism were four 0.1kg ice pucks in the puck deployment mechanism, and at least an equivalent amount of granular salt in the granular delivery mechanism, all while remaining within the total 2.5kg payload capacity of existing multirotor systems commercially available. The final puck deploying mechanism prototype can carry seven pucks, with a total mass of 1.568kg; the final granular delivery mechanism prototype can carry 1.239kg of granular salt, with a total mass of 1.811kg. Therefore, the solution systems are within the multirotor lift capacity.

A series of tests were completed with the two prototypes to ensure that each could properly carry out their intended functions. Although tests with a multirotor were infeasible due to legal/financial issues and time constraints on usage of the existing multirotor system, it was possible to simulate mounting to a multirotor by constructing a test stand. The puck deployment mechanism cycled through its seven pucks repeatedly without failure, and the granular mechanism could effectively contain and deploy its payload of granular salt, in both dry and moderately damp conditions. Range tests were completed in nearby Institute Park to determine the range limit between the transmitter and the receiver mounted to either mechanism, ultimately determining a range in excess of 450m, line-of-sight, with various small obstacles in the way. Given this testing, it is reasonable to conclude that each of the mechanisms would perform as intended when used in conjunction with a multirotor.

Terminology

UAV - Unmanned Aerial Vehicle. A vehicle that is meant to be re-used and has no pilot on board, is controlled via radio, and can carry payloads [1]. May also be autonomous.

UAS - Unmanned Aircraft System. Essentially identical to the term “UAV.” The word “system” refers to the fact that besides the aerial vehicle itself, ground stations or other components may also be present. Term adopted by the FAA [2].

Drone - General term for UAVs or UASs.

FAA - Federal Aviation Administration. United States government agency that regulates the use of private and commercial aerial systems.

Propeller (Prop) - A revolving shaft with two or more airfoils attached that generates thrust. Typically oriented with the shaft along the direction of travel, as in a conventional prop-driven plane [3].

Rotor - A revolving shaft with two or more airfoils attached that generates thrust. Typically oriented with the shaft along the line of increasing altitude above Earth’s surface, as in a helicopter [61]. Often used interchangeably with the terms “propeller” or “prop.”

Helicopter - Aerial vehicle consisting of two rotors, one of which provides lift and direction control, and the other which counters the rotation produced.

Multirotor - General term that refers to any aerial vehicle with more than two rotors.

Quadcopter (Quadrotor) - Aerial vehicle that consists of four rotors.

Hexacopter (Hexarotor) - Aerial vehicle that consists of six rotors.

Octocopter (Octorotor) - Aerial vehicle that consists of eight rotors.

Gimbal - Stabilization device that keeps an object at a fixed orientation. When applied to multirotors, gimbals often take the form of vibration-reducing, camera-pointing mechanisms.

FPV - First Person View. In the world of multirotors, refers to the paired setup of camera and goggles that allow the operator to see a live camera feed, essentially providing the operator with the view that the multirotor has.

1.0 Introduction

Heavy snowfall plagues states across the Northern United States every year. States in the Northeast are generally hit particularly hard with snow. Worcester, MA alone received a total snowfall of 119.7 inches, or 10 feet, in the 2014-15 season. This made Worcester the second snowiest location in the United States for the season, coming behind Lowell, MA by less than an inch [4].

Removing snow from winter roads is only part of the battle. In addition to accumulating on roads, snow also accumulates on the roofs of houses, businesses, and a variety of other structures. When neglected, this accumulated snow is often prone to melting and refreezing before falling off of the roof, thereby forming the ice dams and their accompanying icicles that New Englanders know so well. Such an ice dam is pictured below in Figure 1.

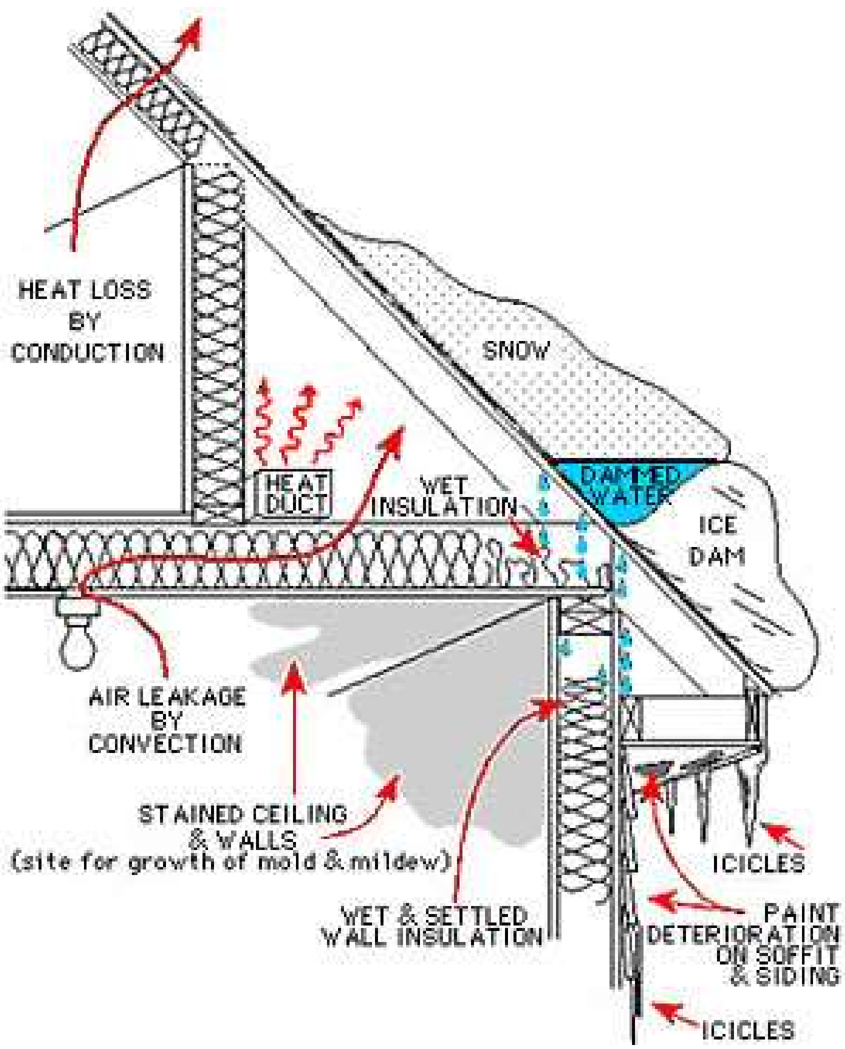

Figure 1. A typical ice dam. [5]

Ice dams are accumulations of ice on roof edges that dam newly-melted snow from further up the roof, preventing it from draining properly. The weight of these ice dams and the dangerous falling-icicle hazards that they promote can pose threats of physical harm to people and animals. These ice dams also pose an array of pernicious financial effects. When meltwater is hindered from draining off the roof, it finds the path of least resistance, and being pushed downward by gravity, leaks through damaged or imperfect sections of roof and into the underlying structure. The resulting water damage to insulation, wood framing, drywall, and various other components, can cost thousands of dollars to rectify, not including the damage done to personal property.

Means of addressing ice dams and the corresponding meltwater already exist in the form of various preventative, control, and removal measures. The focus of the project is on addressing ice dams that already do exist, and when it comes to control or removal measures, there are few viable options. One option is to purchase deicing pucks, which essentially operate by melting channels in the ice dam through which the trapped meltwater can then drain. At present, this method's effectiveness is determined by one's throwing arm and aim, or by the height of the ladder used to more precisely position the pucks, often making this method inaccurate and/or dangerous to the operator. The alternatives are to spend hundreds or thousands of dollars to have a professional service remove the ice, or to risk life, limb, and roof by doing it oneself. And once the next Nor'easter passes through, those ice dams will soon be back in full force and in need of removal once again.

An unlikely technology that is currently gaining worldwide prominence may help to solve the problems and expenses associated with ice dam control and removal. Unmanned Aerial Vehicles (UAVs), also referred to as Unmanned Aircraft Systems (UASs) are most prominently featured in the public eye as war machines that deliver drone strikes. Commercially in the United States, small UASs also make popular remote-controlled toys. These usually take the form of small helicopters, quadrotors, or more generally as multirotors (with any number of props). Businesses and organizations use slightly bigger UASs with great success. Tune in to an NFL game, and you will likely see a UAS with a camera attached flying over the field and delivering close video coverage of the game.

Granted, the main purpose and attraction of these UASs has frequently been to carry smaller built-in cameras for taking pictures and video. However, in relevance to this project, a promising fact about UASs is that, provided a large and powerful enough UAS, the aircraft can carry payloads of varying sizes. Many sport gimbal mounts allow for the mounting of larger cameras and other equipment to UASs, which control the orientation and stabilization of the mounted equipment. Hobbyists all over the world have tailored multirotors to carry non-camera payloads and perform various tasks, using gimbal mounts and/or custom-made apparatuses.

As the popularity of multirotors has increased over the past few years, commercial use and liability issues have become thorny subjects in the United States, and various regulations are already being passed here and in other countries. The use of multirotors will only increase as time passes, with new practical uses being discovered and regulations being fine-tuned and more manageable to work with.

Given the increasing practical capabilities of multirotors, and the unrelenting issues posed by ice dams, this project aims to design and construct a payload for a multirotor that will address the aforementioned problems associated with ice dams. The specific purposes of the payload shall be to first promote and improve the ability of meltwater to drain from behind the dams, and secondly, to gradually melt the ice dam as a whole. These efforts are part of a two-step process to clear winter roofs, using a conventional "roof rake" to remove the snow, and this "aerial roof rake" system to remove the ice dam once it has already formed.

A standard design process was implemented by the project. This process is briefly outlined below.

- Identify Need
- Background Research
- Goal Statement
- Task Specifications
- Ideation/Invention
- Modeling and Analysis
- Solution Selection
- Detailed Design
- Prototype
- Test

2.0 Identification of Need

This project aims to enable the draining of meltwater trapped behind roof-top ice dams, and to gradually eliminate ice dams in their entirety.

3.0 Background Research

3.1 Ice Dams and Their Effects

For centuries, ice dams have presented problems to homes and homeowners, predominantly in areas where frequent seasonal snowfall and below-freezing temperatures occur. Although the ice formations themselves usually do not directly compromise homes, the melted snow (meltwater) that builds up behind them can. When prevented from draining, this meltwater leaks through roofs, causing water damage. This damage requires costly repairs and often recurs when measures are not taken to abate and prevent the ice dams. Ice dams and their icicles may look pretty, but they demand serious attention from homeowners.

Refer back to Figure 1 in Section 1 for an illustration of a typical ice dam. Ice dams form when the upper portions of a roof have above-freezing surface temperatures, and the lower portions have below-freezing surface temperatures. Given a poorly insulated and air-sealed roof, and several days of subfreezing ambient temperatures, only one or two inches of accumulated snow are needed for ice dams to form [6]. The root cause of ice dam formation is heat that escapes from the interior of the home, conducting through drywall, wood, and ceiling insulation, before reaching the attic where it then convects toward the roof. If the roof is poorly insulated, this heat conducts through it to the outside air.

When this heat transfer raises the roof's surface temperature above 32^{o} F, snow that is lying on these portions of the roof melts and flows toward the eaves. These eaves are typically a foot away from the house, and therefore do not receive significant amounts of stray heat from the attic and heat duct areas. Therefore, the roof edges generally remain below 32^{o} F, causing the meltwater to refreeze when it reaches these portions of the roof. Over time, meltwater originating from heated portions of the roof continues to run onto and refreeze on the eaves, thereby forming ice dams.

As the ice dam grows, it eventually covers the entire eave. At this point, the remaining portions of the roof are the heated portions from which meltwater is originating; this meltwater begins to collect behind the dam, and the heat conducting through the roof from the attic and heat duct areas keeps this meltwater water from re-freezing. Since the ice dam prohibits water from dripping off the edge of the roof, the meltwater inevitably finds the path of least resistance and begins leaking through the roof, ultimately coming in contact with interior wood, insulation, drywall, and personal items. This leakage causes wood rot, damage to insulation and drywall, and mold and mildew growth [5].

As insulation becomes soaked with meltwater, it thins or compresses, resulting in lower effective R-values and a diminished capacity to retain heat. Conversely, as snow continues to accumulate on the roof, it serves as insulation and its capacity to retain heat increases, causing heat directly beneath the snowy roof to become trapped. With diminished insulation between the house interior and attic, and increased insulation between the attic and roof exterior, more heat builds up in the attic, thereby promoting further meltwater formation, and ultimately, greater resulting home damages [6].

3.2 Ice Dam Prevention, Control, and Removal

In order to temporarily halt or even prevent meltwater leaks and the severe resulting damages that they are capable of causing, homeowners can take a variety of different measures, ranging from preventing ice dam formation in the first place, to controlling and/or all-out removing ice dams. For the sake of clarity in the following section of the report, these measures are divided into three categories: 1) Ice Dam Prevention, 2) Ice Dam Control, and 3) Ice Dam Removal.

3.2.1 Ice Dam Prevention

This first category presents measures taken by homeowners to prevent ice dam formation, or at least largely diminish their potential impact, well before snow and ice hit (with the exception of the last method). Research yielded six common measures taken to prevent the formation of ice dams.

Ensuring Adequate Attic Insulation

Adequate attic insulation is essential to keeping heat in the living areas of the house, out of the attic, and consequently, away from the roof. To ensure that the insulation used is sufficient for preventing heat loss, homes in the northern United States should have ceiling insulation with an R-value of 38 (R-38) or greater. Additionally, this ceiling insulation should be continuous and consistently deep about the entire ceiling area [6]. The less heat that escapes from the house and into the roof, the less likely that different portions of the roof will be above and below freezing, and the less likely that ice dams will form. In addition to preventing ice dam formation, adequate insulation can help homeowners to save significantly on home heating costs [7].

Ensuring Optimal Roof Ventilation

In some cases, including cases where seemingly adequate insulation has been installed, heat still escapes from the house and into the attic. To diminish the amount of heat that builds up in attics and ultimately promotes meltwater leaks, proper roof ventilation should be ensured. An adequately-designed roof ventilation system allows air to move through the attic and rafter spaces, preventing warm air from building up in the attic. To ensure an effective ventilation system, the total free intake area venting to the attic must be greater than or equal to the total free exhaust area venting from the attic. Additionally, half of the venting area should be placed high in the attic (for exhaust), and the other half should be placed low in the attic (for intake). This placement allows for a continuous flow of air that moves from the bottom to the top of the attic [8].

Sealing and Insulating All Ceiling Penetrations

Common household fixtures such as bathroom fans, plumbing vents, and recessed ceiling lighting can allow large amounts of warm air to escape from living areas and into the attic when improperly sealed. By taking time to properly seal these fixtures, the amount of warm air escaping to the attic will be reduced, thereby lowering the risk of ice dam formation. On this note, recessed lighting, also known as lighting cans, should be used sparingly, or avoided if possible. Lighting cans generate an excessive amount of heat, and when improperly sealed, can release significant heat directly into the attic, ultimately promoting meltwater and ice dam formation.

Installing Heat Tape and Heat Cables

Figure 2. Heat cables installed along the edge of a roof. [9]

The installation of heat tape or heat cables along the lower portions of the roof (along the edge) can help to reduce ice dam formation. A typical installation is shown in Figure 2. It should be noted that when such cables are improperly installed and/or used, they can present fire hazards and create a backflow of meltwater that worsens roof leaks. Additionally, heat cables are essentially useless if the structure on which they are installed has severe insulation and ventilation problems. When these insulation and ventilation problems exist, it is likely that meltwater leaks will occur well above the edge of the roof, or in the area where the heat tape itself lies, where ice dams would otherwise form [7].

Maintaining Clean Gutters

Contrary to common belief, gutters do not directly cause ice dams. In fact, they can help to prevent ice dams when properly maintained. The function of gutters is to collect water from the roof and channel it to the ground. When filled with leaves, twigs, and other forms of clutter, gutters cannot effectively channel meltwater that does reach them. Thus, in the winter, any meltwater that does reach a clogged gutter will not be able effectively channel off of the roof and will be prone to freezing in the gutter. Once gutters are completely clogged with clutter and frozen water, they can no longer drain water and ice dam formation is thereby propagated [6].

Removing Snow from the Roof

Figure 3. A roof rake device. [10]

Recall from earlier that ice dams and the meltwater that collects behind them are the result of roof-top snow being heated, and thereby melted. With this being said, if there is no snow on the roof, there can be no meltwater. Therefore, homeowners or snow removal services can use roof rakes and shovels to remove snow from roof tops. Roof rakes are typically safer and more effective, as they can be operated from ground level and are designed specifically for the task of roof-top snow removal. These devices are simple, typically comprised of a long pole attached to a horizontal sheet, as pictures in Figure 3. Pushing the device's head under the snow and advancing up the roof, the snow gets forced over the sheet, and subsequently slides down it and off the roof.

If snow is removed before an ice dam forms, then the ice dam and meltwater will be avoided altogether. Even if an ice dam has already formed, when snow is removed, the problem of further meltwater generation will be eliminated and only the dam will remain. Either way, using a roof rake to remove snow from a roof is an effective way of preventing ice dams and the meltwater that first causes, and then gathers behind them.

3.2.2 Ice Dam Mitigation

In many cases, even the best preventative measures cannot guarantee total ice dam prevention, and in many cases, homeowners do not have the time, money, and/or desire to take preventative measures in the first place. When ice dams do form, they must first be controlled, and all-out removed if possible or deemed necessary. Controlling an ice dam entails enabling the built-up meltwater to drain from behind the dam, in order to keep it from leaking into the house. Common and effective measures for draining meltwater are described here.

Placing Deicing Pucks

This method entails placing deicing pucks both behind and on top of the ice dam. Deicing pucks are small, cylindrical units of compacted salt, that salt most commonly being calcium chloride ($CaCl_2$). Pucks are typically two or three inches in diameter and one inch in height, and are available in prepackaged quantities at local hardware and home improvement stores. A common brand found either online or in the Worcester area is Roofmelt Ice Melt pucks, which is available in 60-puck containers at Home Depot and Lowe’s [11].

The puck product is intended to be tossed onto a roof, ideally landing directly behind the ice dam. Composed of calcium chloride, these pucks react exothermically with water, helping to melt the ice it lands on. This ultimately allows the puck to sink down to the roof, where it comes in contact with dammed meltwater. The puck mixes with the meltwater, forming a brine solution that comes directly in contact with the wall of the ice dam. This brine solution has a lower freezing point than the ice in front of it, preventing it from freezing as well. Coupled with the exothermic reaction that calcium chloride undergoes in contact with water, the mixture increases the rate at which the ice dam melts, ultimately eliminating the dam and allowing the meltwater to drain off of the roof [12]. The more pucks thrown behind the dam and the more area covered, the faster the rate at which the dam will melt. A typical arrangement is shown in Figure 4.

Figure 4. Ice melt pucks placed along an ice dam. [13]

The method previously described, while increasing the melting rate of the ice dam as a whole, does not address the immediate need of allowing meltwater to drain from behind the dam. In order to sufficiently drain meltwater and stop roof leaks, channels must be formed in the ice dam. To achieve this, a ladder must typically be used to manually place pucks on top of the dam. Pucks should be placed collinearly, parallel to the slope of the roof, spaced approximately two to three inches apart, and in quantity to cover the entire width of the ice dam (the dimension parallel to the slope of the roof). These individual lines of pucks should be spaced approximately four to five inches apart along the entire length of the ice dam.

As each of the pucks melt the ice below and around them, they sink through the dam and ultimately reach the roof. Upon reaching the roof, gravity causes the pucks to begin progressing downward along the slope of the roof, melting the ice in front of them and ultimately reaching the edge of the roof. As the pucks reach the edge of the roof, channels through the ice have been formed behind them; collected meltwater can then flow through these channels, thereby draining from behind the dam and stopping leaks into the house [13].

At present, both of the methods described above require the user to either toss the pucks onto the roof from ground level, or to access the roof via ladder or other means to manually place the salt pucks. Tossing pucks onto the roof does not guarantee accurate or optimal placement, and manually placing pucks on a roof presents substantial falling hazards that can lead to serious injury or death [14]. Given the effectiveness of these methods, a means to exercise them in a safer, more effective way would be ideal.

It should be noted that calcium chloride can pose some health threats to both vegetation and pets alike. While less toxic to plants than sodium chloride (also known as rock salt), calcium chloride can be extremely harmful to pets if contacted or consumed in large quantities [15][16]. Calcium chloride is a common salt puck composition, so the owners of pets should exercise caution.

Placing Permeable Deicing Units (AKA Trough-makers)

This method works similar to the deicing puck method in that it involves creating channels through which meltwater can flow. This method involves placing a permeable filter, containing a salt core (either calcium chloride or magnesium chloride) in the meltwater on top of the ice dam. Unlike deicing pucks, these filters are not commercially available, but can be made easily by filling a pantyhose with granular salt. The pantyhose serves as the permeable layer.

When placed on top of the dam, the filter functions much like a deicing puck, releasing heat on contact with the ice and melting it, thereby creating meltwater that penetrates through the permeable layer and into the salt core. This creates a brine solution with a lower melting temperature than the ice, remaining as a liquid and helping to melt the ice dam. As the filter sinks into the ice dam, a channel forms and gradually increases in depth until the filter reaches the roof. These channels allow meltwater to drain from behind the dam. To improve effectiveness, multiple filters, spaced four to five inches apart, should be placed parallel to the slope of the roof over the entire width of the ice dam. In order to accelerate the formation of a brine solution, water should be poured over the filters after they are placed over the ice dam.

In an experiment conducted by a home inspector, one week after placement of several trough-makers, none of them had made even a dent in the ice dam. This was likely due to the fact that the temperatures were near-zero for the entire week, making it difficult for the salt to sufficiently release the requisite heat to melt the ice and form a brine. Therefore, while this may be an effective method in theory, it is potentially very temperature-sensitive and overall not nearly as effective as deicing pucks [13].

3.2.3 Ice Dam Removal

After first controlling ice dams (providing a means for the collected meltwater to drain), many homeowners wish to completely eliminate ice dams. A variety of measures can be employed to achieve this. Most commonly, these measures include steam blasting and manual removal. Granular deicing agent may also be used (as it is used widely on roads and sidewalks), but this results in a much slower melting process.

Removal by Steam Blasting

Commercially, steam blasting is the most common method for removing ice dams. This method involves using a steam blaster to spray steam onto the ice dam. As pressurized steam lands on the ice dam, it quickly melts the ice, ultimately eliminating the entire dam in a matter of hours, depending on the size of the dam [17]. When maintained and used properly, steam blasters can generally remove 10 to 15 feet of ice dam per hour [18]. This method does not structurally compromise the roof, whereas manual removal by hammer and ice pick can cause significant roof damage [19]. Many companies offer steam blasting service but it can be very expensive; some estimates range between $425 and $825 per hour [20]. Two customers in Massachusetts report paying $475/hr [21]. Prices are typically determined on a case-by-case basis. Several steam-blaster ice dam removal services cater to the Worcester area, including Lavallee Home and Property Services, Perfect Power Wash LLC, and Quality Cleaning and Restoration [22][23][24].

Manual Removal

In contrast to the steam blasting method, this method entails using hammers, ice picks, shovels, and other manually operated tools to remove ice dams. This method is more prone to causing roof damage (particularly to shingles) and is the most dangerous and time-consuming method for removing an ice dam [19]. Given the dangers associated with this method, homeowners are encouraged to hire professionals to remove ice dams in this manner. One ice dam removal service in the Worcester MA area that performs manual removal is Nor’easter Roofing Inc. [25].

Removal by Continuous Deicing Agent Application

Another possible method for removing an ice dam is to continuously coat the ice dam, both on top of and behind the dam, with a granular deicing agent. Similar to deicing pucks, this deicing agent melts the ice and forms brine with a decreased melting temperature from the ice that it contacts. Whereas deicing pucks are more effective at forming channels for meltwater to drain through, granular deicing agent can be more easily spread over large areas, quickly covering more dam surface area and promoting ice melting over the entire structure. In order to ensure continual melting of the dam, several coats of granular deicing agent may need to be applied over time.

Given that granular deicing agents are more easily spread, they are more prone to contaminating large areas than deicing pucks. Additionally, whereas deicing pucks are designed for use on roof surfaces, many granular agents are designed for use on steps and walkways. Therefore, it is important to ensure that the granular agent used is safe for pets, vegetation, and building materials. Granular deicing agents labeled as “pet-safe” should be used, as they do not harm pets or vegetation, and do not compromise common building materials. These pet-safe agents are most commonly composed of a substance known as Urea (also known as Carbonyl Diamide or Carbamide Resin) [26] or Magnesium Chloride. Pet-safe granular deicing agents are available for order online or at local hardware stores.

Despite its potential for effectiveness, this is the slowest method for directly removing an ice dam. Whereas the previous two removal methods can be completed between several hours and a day’s worth of time, and will immediately relieve any dammed meltwater, this method will take significantly longer and will not immediately relieve meltwater. Therefore, when this method is exercised, channels should first be formed in the dam via deicing pucks or trough-makers. This ensures that meltwater is drained from the dam as quickly as possible, thereby eliminating roof leaks. It is important to remember that rather than the ice dam itself, the dammed meltwater and corresponding roof leaks present the largest threats to the roof and underlying structure.

3.3 Multirotors

Ice dams may be prevented, mitigated, or outright removed via a host of time-consuming or expensive measures. Once an ice dam has already formed, mitigation is the primary goal. Mitigation is the least-developed option of the three, relying on salt to form troughs. The only alternative (once a dam has already formed) is removal, which puts one at risk of falling off ladders or damaging the roof, or requires paying others to professionally remove them.

As a more rapid, safe, and cost-efficient way of ferrying de-icing salt to the roof, multirotors were explored as a deployment vehicle. Multirotors are a type of UAV (or “drone”), most commonly operated using a transmitter within line-of-sight. The use of a multirotor allows operation from ground level, with no risk of slipping off of a roof or being hit by falling ice. An emphasis on the process being fast and cheap could allow a business to be formed around this strategy.

While choosing an adequate multirotor platform, emphasis was placed on ease of use, flight readiness (out of the box), payload capacity, and number/type of potential payload mounting points. The presence and location of landing gear, as well as prop guards to prevent damage when flying close to a roof, were also taken into consideration.

Preliminary research into multirotors showed that “heavy payload” usually only entails about 1kg of payload. Most readily-available multirotors are not made to handle high payloads. In theory, the selection and assembly of individual components allows for higher payloads (as demonstrated by HobbyKing’s annual Beer Lift competition [27]).

Efforts were directed at the development of a multirotor payload and not at the development of a multirotor itself, so this method was not considered. For purposes of redundancy and cost effectiveness, it was decided to design for the multirotor that another MQP team on campus had previously obtained. The decision-making process before this conclusion was reached is shown in Sections 3.3.1 through 3.3.4.

3.3.1 DJI Phantom 3

Figure 5. The Phantom 3 Quadcopter, sold by DJI. [28]

Perhaps the most ubiquitous drone currently on the marker is the DJI Phantom, shown in Figure 5. The newest Phantom 3 is a quadrotor available for $800 standard [28]. The older Phantom 2 costs $500 standard and has much the same form factor [29]. Both have gimbal mounts used for attaching a DJI camera or GoPro.

The most attractive thing about the Phantom is that it is a ready-to-fly system. It comes with a proprietary battery and controller, and all the flight electronics are integral to the structure of the aircraft. However, the only payload a Phantom can carry is its small camera or an equivalent mass (and many Phantom bundles include one). While the Phantom 3 does not list a technical specification in this regard, the similar Phantom 2 has a mass of 1000g and a takeoff weight of less than 1300g [29]. The drone cannot handle more than 300g of payload, while a single Roofmelt ice puck has a mass of approximately 100g.

This was deemed the least versatile platform for salt dropping operations. With such a low payload, including the salt dropping mechanism mass and the need for a small camera to gain any precision dropping ability, not much actual salt may be lifted with this platform.

3.3.2 3D Robotics X8+

Figure 6. The X8+ Octorotor, sold by 3D Robotics. [30]

A company called 3D Robotics (3DR) used to sell this drone for approximately $1350, but it is now only available from secondhand sellers for around $1000 [31]. This multirotor - an octorotor configuration with two rotors per arm - does not include a gimbal upon which a camera may be mounted, but there are many mount points on the body. It is pictured in Figure 6.

The X8+ shares the biggest boon of the DJI Phantom: Its flight readiness. All of the required accessories are included, such as a transmitter and batteries. Its payload is higher as well, at 800g recommended and 1000g or over with flight time reduction. As a puck-deploying platform, this multirotor could hold four or five pucks, with the remaining 500-600g of mass taken up by the mechanism itself.

There are too many drawbacks to this vehicle to recommend it as a platform. The flight time is only up to 15 minutes. Reliability may be a problem, with one reviewer noting that “75% of flights go wrong in some way” [32]. The arrangement of the props is concerning, as mounting a mechanism to the bottom of the body must be done carefully. As of November 2, 2015 the product was still available for purchase, but is now only available through secondhand sellers as mentioned above [33].

3.3.3 DJI S900

Figure 7. The DJI S900 hexarotor, sold by DJI. [34]

The DJI S900 is marketed as a hexarotor professional camera platform. As such this multirotor comes in many configurations based on the need, ranging from $1400 for just the frame, to $3800 for the frame, flight controller, and camera gimbal [35]. This setup is not ready-to-fly. At a bare minimum, it still requires a battery and charger, flight controller (which controls the speeds of the motors in response to an input), and receiver/transmitter combination (for control). The various configurations in which this multirotor is sold usually include variations of flight controller, receiver, and gimbal only.

However, the payload of this design is highly desirable. A takeoff mass of between 4.7kg and 8.2kg translates to a maximum possible payload of 3.5kg [34]. This assumes that the 4.7kg takeoff mass includes the mass of all required components and the multirotor. A factor of safety of 1kg may be employed for any components not included in this estimate, making the design payload decrease to 2.5kg. A flight time of approximately 18 minutes (with a 6.8kg total mass) makes it a middling choice in this regard.

This multirotor would make use of the gimbal mounting points. A camera is mounted to these gimbal mounting points in Figure 7. The landing legs are retractable, extending down for landing and retracting when airborne. Payload height would be constrained by the height the multirotor sits off the ground at landing.

The mechanisms were designed with this multirotor choice in mind.

3.3.4 DJI S1000+

Figure 8. The DJI S1000+ octorotor, sold by DJI. [36]

This octorotor platform - the big brother of the DJI S900 - is the same in virtually every respect except for the addition of two rotors and the increased payload they grant. Pricing goes anywhere from $1900 for solely the frame, to $4550 to a bundle that includes a top-of-the-line flight controller, receiver, and gimbal [37].

A takeoff mass of between 6.0kg and 11.0kg results in a maximum possible payload of 5kg [38]. As above, a factor of safety of 1kg may be employed, taking into account the addition of any components not included in this specification; so, a maximum payload of approximately 4kg should be expected. An extra 1.5kg is gained with this multirotor over the S900, although the flight time decreases to 15 minutes at 9.5kg takeoff mass. It retains the same retractable landing legs, between which the payload would be mounted.

The other project on campus uses this multirotor, which is very similar to the S900, especially with regards to the mounting situation. As a result the mechanism designs did not require modification to fit on this alternative vehicle.

3.3.5 Feasibility of Select Multirotor Modifications

While researching multirotors, a few modifications extending the abilities of the system were proposed. Their feasibilities are discussed briefly here.

Powered Tether

The S900 has six 40A ESCs (Electronic Speed Controllers) that interface with the six motors. At absolute full power, the current load is therefore 240A. The multirotor's recommended 6S LiPo battery (six-celled lithium-polymer battery, at 3.7V per cell) will output 22.2V. A powered tether would have to output 22.2V 240A power, with the capability to rapidly fluctuate as the demands of the motors change. Use of the S1000+ would only increase this demand.

Most power supplies cannot handle this (interview with Joseph St. Germain, 02 Nov 2015, Appendix B). In order to make this feasible, the power supply should instead power a ground-based battery which provides the flow of current through the tether. Larger current results in a larger diameter wire required. For this application, a 000 or 3/0 AWG (American Wire Gauge) wire would be required, with a diameter of 0.41in [39]. The weight of such a wire would be prohibitive to the payload capacity of the multirotor, which can fly for a solid 15 minutes untethered (using the recommended 6S 15000mAh LiPo battery) anyways.

Prop Guards

Adding prop guards adds weight to the design. The S900 has six rotors to protect, while the S1000+ adds two more. Changing or loading of mechanisms will be done with the quadrotor fully powered off. We do not expect much time on the ground, given that the action of reloading requires either sliding out the mechanism and loading four pucks (puck mechanism), or sliding out the mechanism and pouring in salt (granular mechanism). So, such guards may be unnecessary.

However, a minimalistic guard (like a stiff wire surrounding the vehicle) may add minimal weight and still prevent a close call, should one occur. This option was not developed due to the project's lack of multirotor availability.

3.3.6 Legality of Multirotor Use

The legality of multirotor use in the US changes between recreational, commercial, and public use. Public use requires a Certificate of Waiver or Authorization (COA), and may only be granted to public entities such as publically-funded universities (while WPI is privately funded). However, a COA may be required for private operations as well [40]. As it is unlikely that use at WPI constitutes either of these, the remaining two categories will be discussed.

MQPs constitute multirotor use for education. It is unclear whether this falls under private or recreational use, so a COA may be necessary. If it is simply recreational use, there are safety guidelines that must be followed in the operation of the multirotor. For example, a maximum altitude of 400ft is allowed, flight within 2 nautical miles of a heliport is disallowed, and flight within 5mi of an airport must be approved by the local control tower [41]. As of 21 Dec 2015, the FAA also requires the registration of any “model aircraft” between 0.55lb and 55lb. Above 55lb is not allowed [42] unless the aircraft is certified by a community-based organization [43].

Commercial use refers to the use of a UAS for any business purpose - professional, contract, or for compensation in general [44]. The regulations regarding use here are rather vague; to be safe, a Section 333 exemption should be filed. These are granted on a case-by-case basis by the FAA and allow commercial use [45], but take some time to process.

The regulations in the US for multirotor use are not very clearly defined, and are in fact rather restrictive for anyone not using their multirotor as simply a toy. Most people by now know of the excitement that Amazon Prime Air multirotor package delivery has caused, yet Amazon is still subject to the restrictive and vague regulations by the FAA. The industry is being hamstrung by the current state of the law.

Around the world, multirotor use is increasing in response to more clearly defined or un-restrictive regulations, and the promise that UAVs hold as a technology. For example, Special Flight Operations Certificates (SFOCs) were required to operate multirotors in Canada (similar to Section 333 exemptions in the US), until a 27 Nov 2014 law granted blanket exemptions for “...’very small’ 2kg (4 lb., 6.55 oz.) UAVs and ‘small’ 2 to 25kg (55 lb., 1.8oz.) UAVs that would eliminate the need for an SFOC if certain conditions are met” [46]. Regulations are not as advanced in Russia, and yet experiments such as a company using drones to fly banners for a restaurant at lunch time have met great success. Similarly, a company in Brazil took advantage of the technology in the holiday season of 2014, advertising its clothing with flying mannequins wearing it [46].

It is clear that if a business plan were to be pursued as a result of the project, a Section 333 exemption would be required. Solely education-related use is less clear. Ultimately, the issue may be one of liability. An individual (e.g. a faculty member) could purchase and register a UAS for their personal recreational use and “allow” students to use it; or the university could buy it, in which case a Section 333 exemption and/or a COA may be required. Either way, the purchasing party is the one liable for any damages that result from the use of the multirotor.

4.0 Goal Statement

The goal of this project is to develop a multirotor-mounted system which drops Roofmelt salt pucks and granular pet-safe ice melt.

5.0 Task Specifications

1. The system carries both standard Roofmelt Ice Melter Tablets (i.e. deicing pucks) [11] and pet-safe granular ice melt [47]
2. The system carries a minimum of 4 deicing pucks per-run
3. The system carries a minimum quantity of granular salt equivalent to the mass of 4 deicing pucks
4. All components of the system are be corrosion-resistant to water, Calcium Chloride, Magnesium Chloride, and Urea
5. If the system is composed of multiple mechanisms, they must be rapidly interchangeable
6. The system is manually-controlled from a ground controller
7. The system uses line-of-sight operation
8. When mounted on the multirotor, the system (one mechanism and its corresponding full load of salt) does not exceed a mass of 2.5kg
9. The center of mass of a mounted mechanism remains within 0.5in of the center of mass of the multirotor, to the left or right of the forward-pointing pitch axis
10. The system is powered and controlled independently of the multirotor
11. The Transmitter/Receiver combination avoids the 5.8GHz frequency, to avoid interference with the multirotor's pre-existing control system
12. The Transmitter/Receiver combination has at least two programmable channels
13. Each mechanism comprising the system uses a maximum of two actuators
14. The system mounts to the multirotor using the multirotor's gimbal mounts
15. The system may be mounted/dismounted from the multirotor without the use of tools (hands only)
16. The system may be reloaded without the use of tools

6.0 Development of Preliminary Designs

6.1 Preliminary Designs

Many design concepts were developed over the course of the project. Specific emphasis was placed on ease of reloading, ease of removal from the multirotor, manufacturability, and payload capacity. Many were given internal names if they bore similarity to common objects.

6.1.1 Design 1 - Vertical Tube with Shelves

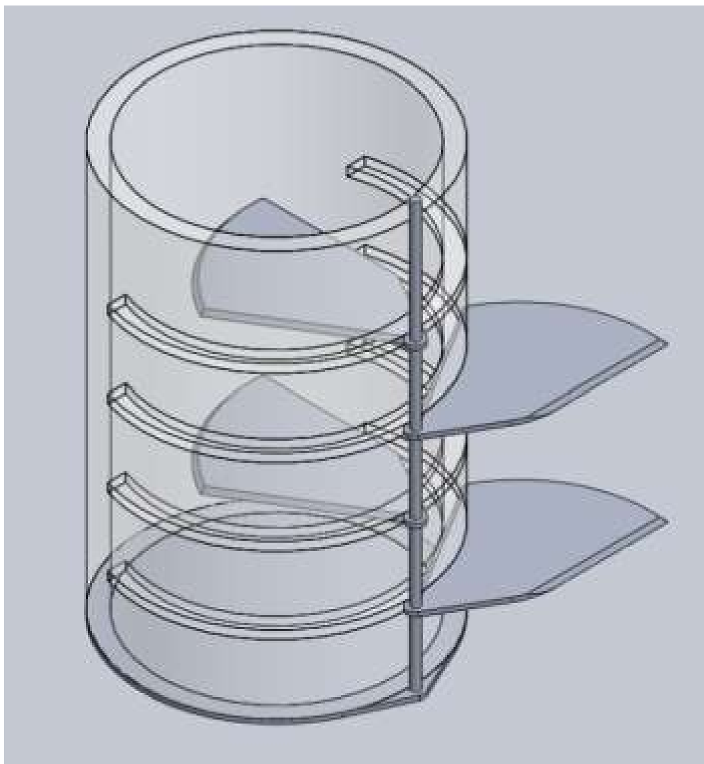

Figure 9. Design 1.

This was one of the earliest design concepts, and would be used for dropping Roofmelt ice pucks. Pictured in Figure 9, the device consisted of a vertical tube storing approximately four pucks, with a rotating shaft along the side. This rotating shaft would be used to turn “shelves” that hold the salt pucks and cycle them down through the mechanism by gravity. These shelves were oriented 90 degrees to each other down the rotating shaft. One set, with the shelves two puck-widths apart, would remain inside the tube while the other set would be outside it. Rotating the shaft back and forth 90 degrees would cause the shelves to switch between being in or out of the tube, and the pucks to drop down one space each time, eventually resulting in a drop from the lowest level. Seen from a single puck’s perspective, the shelf supporting it would drop out from under it just as another shelf rotated in its way, one puck-height below (unless that puck was on the last layer of the device, in which case it would fall completely out the bottom aperture).

An inherent problem of this design is the reliance on the timing being “just right” so that one falling puck would not be accompanied by another above it due to its supporting shelf not rotating underneath it in time. To rectify this, the shelves were offset by less than 90 degrees to each other, and their shape was changed from a straight blade to a curved one. In this way, as one puck’s shelf rotated out from underneath it, the shelf above it would already by supporting the next puck, preventing a premature drop.

However, the shelves had to be shaped as “blades” so that consecutive pucks could be wedged apart as the shaft rotated between them. Standard roof-melt ice pucks are irregularly-shaped disks, but are largely flat on their horizontal surfaces. An inability to separate consecutive pucks could result in a stalled motor or a broken mechanism. This design was deemed infeasible.

6.2.2 Design 2 - Swivel Arm

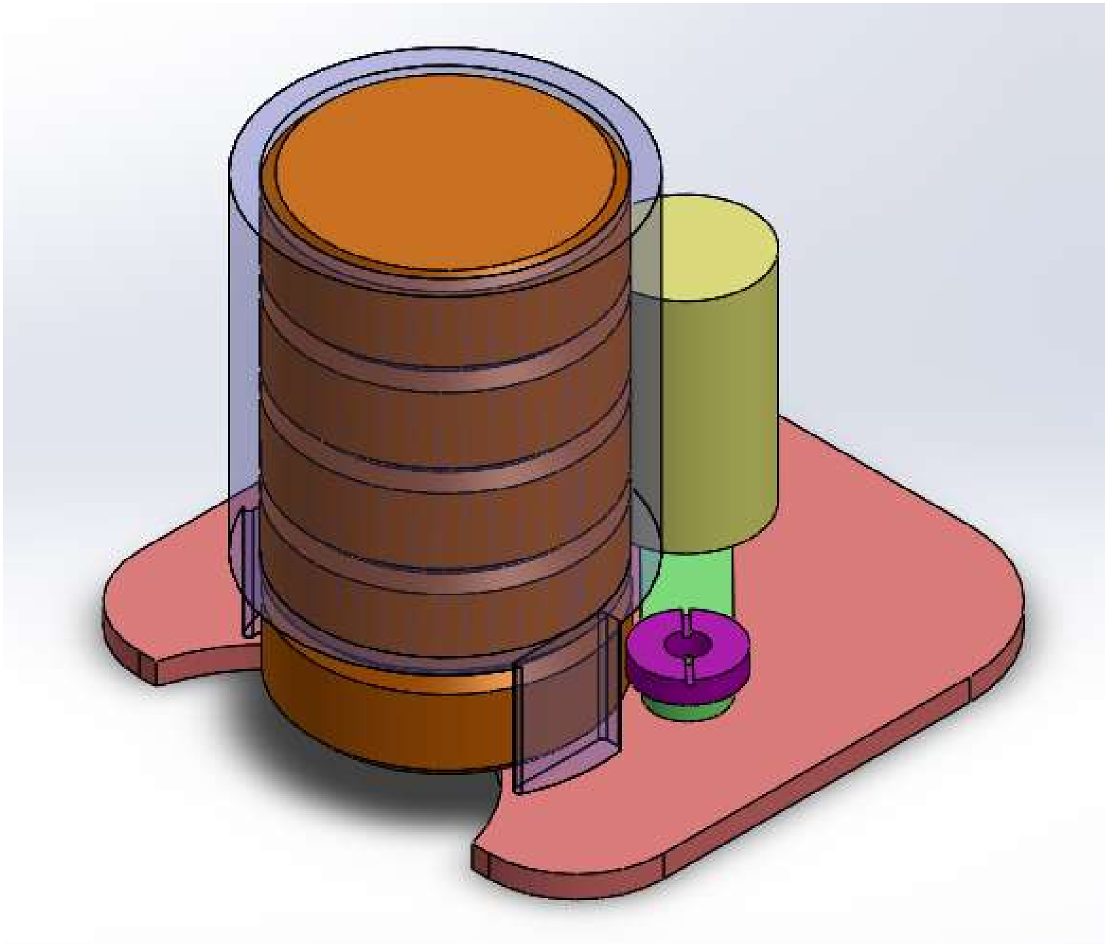

Figure 10. Design 2.

The “Swivel Arm” design was created in an effort to remove the need to separate the pucks individually, as in Design 1. This new design featured a rotating arm with a roller affixed to the end. The arm featured in this design would be driven directly by a servo motor with endpoints on either side of the puck storage tube. Rotating the servo from one extreme to the other would cause the device to release a puck. The device itself consisted of a bottom plate that supported the servo motor, swivel arm, and pucks. These pucks were stored vertically with a storage tube. This is a major benefit, as the number of pucks stored is reliant only upon the weight of the stack vs strength of the arm actuator, and the height available under the multirotor.

The version of this design pictured in Figure 10 was able to hold five pucks. A shift from one arm position to the other would cause the roller to interact with the loaded puck and eject it from the device. This would in turn allow the next puck to lower into the loaded position. In order to ensure that the pucks would always follow the same ejection path, the storage tube on either side of the loaded puck was extended as a guide. The unintended result of this is that the force exerted by the swivel arm perpendicular to the release direction would cause the puck to collide with the walls. This effectively limited the pressure angle of the puck-roller interaction and therefore the length of the swivel arm itself.

Because it had to have a reduced length, the swivel arm would not be able to properly eject pucks unless material was removed from below the loaded puck, but by removing this material, the risk of pucks falling out of the “ready” position prematurely was introduced. The swiveling arm would be subject to the weight of all the pucks above it while cycling as well, potentially resulting in jams. While the design itself was simple, it would need further modification to become feasible.

6.2.3 Design 3 - Crank-Slider

Also incorporating a vertical tube used to hold pucks, this design looked and functioned similar to the previous, pictured in Figure 10. The key difference was the use of a crank-slider linkage instead of a single small arm, pushing each puck off individually. The slider itself acted as the shelf upon which the second puck would rest as the first was dropped, preventing multiple-drops or jams.

This design was largely feasible, but did have a major drawback. With the puck-to-be-dropped resting upon the bottom horizontal plate, there was still nothing to stop it from falling prematurely due to movement of the entire mechanism (the plate would be parallel to the Earth’s surface, mounted on the bottom of an ostensibly multi-axis-mobile multirotor). Ideas such as doors held shut by springs or servos were also devised. All of these extras requiring space at the bottom of an approximately 3in-wide tube did not bode well for the manufacturability of the mechanism.

6.2.4 Design 4 - Rack and Pinion

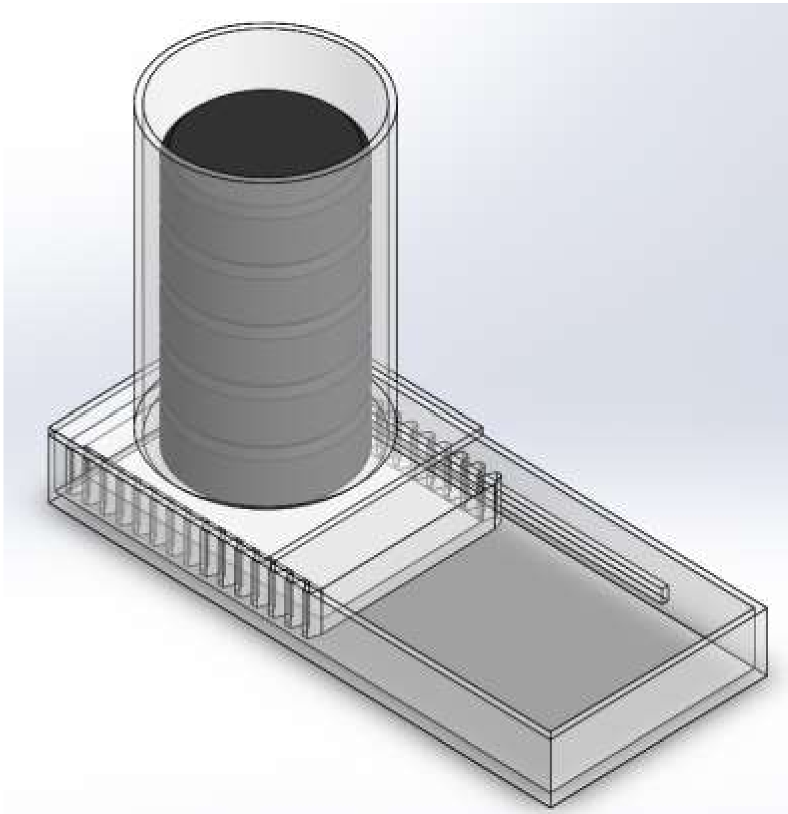

Figure 11. Design 4.

This design was an evolution of the previous one, aiming to solve its premature drop issues. It made use of a similar storage tube for holding roughly four or five roof melt pucks, but rather than using a crank-slider to cycle the pucks, it used a rack and pinion system. This design, shown in Figure 11 and aptly designated the “Rack and Pinion,” would use the rack as an indexing shelf. Along the side of the mechanism would reside a gear train and a motor or servo, used to slide the rack back and forth within a guide as the motor turned.

In its extended position, the rack would act as a base for the stored pucks to rest on. When retracted, a puck would fall into position in front of the rack, ready to be ejected. By returning to the extended position, the rack would both eject the puck and support the rest of the pucks above it once again. This design makes use of the weight of the stored pucks to ensure that the puck in the ejection position wouldn’t be released prematurely.

However, the sliding action of the rack created concerns that a buildup of residual salt from the Roofmelt ice pucks could cause problems with the mechanism. This could result in jams and a broken motor. The number of moving parts introduced by the need for a gear train was also deemed to be a potential problem for consistent operation.

6.2.5 Design 5 - Turntable

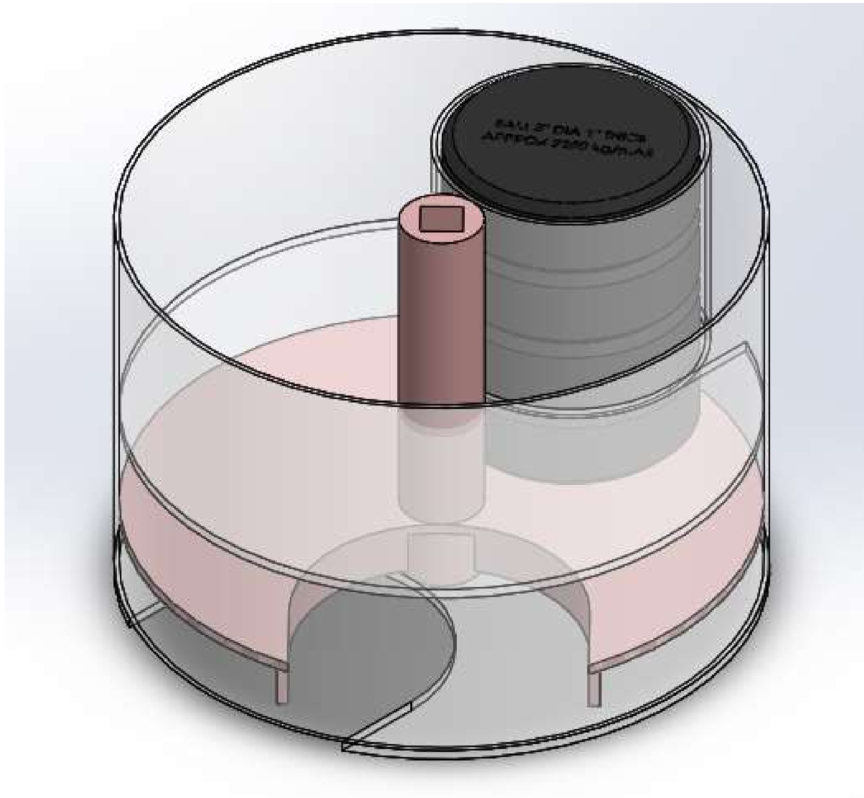

Figure 12. Design 5.

A later design was created by utilizing a rotating base plate and was given the descriptor "Turntable," pictured in Figure 12. This design placed a tube of vertically stacked pucks above a rotating plate with a notch cut into it. Pucks would fall into the notch at a rate of once per revolution and would travel 90 or 180 degrees around a lower channel before being dropped out of the device through a bottom hole (Figure 12 shows the 180-degree orientation, determined by the location of the vertical puck storage tube). This design was conceptualized in order to both stop pucks from falling out prematurely, and move them from the storage to release points.

The Turntable made use of a single driven shaft to control the motion of the entire device. The outer shell was stationary and provided a guide and protective body for the pucks as they were transported from the storage to ejection positions. The inner rotating shaft and table provided the driving force behind the movement of the pucks. While this design was comparatively simple and straightforward, it suffered from the drawbacks of large physical size and relying on the loaded puck and turntable to hold stored pucks in place. Because of this, sliding friction between the stored pucks and other aspects of the design during operation would create a buildup of waste salt and excessive torque on the driving servo. This salt could potentially cause the device to jam and fail mid-flight.

6.2.6 Design 6 - Turbo Puck Release

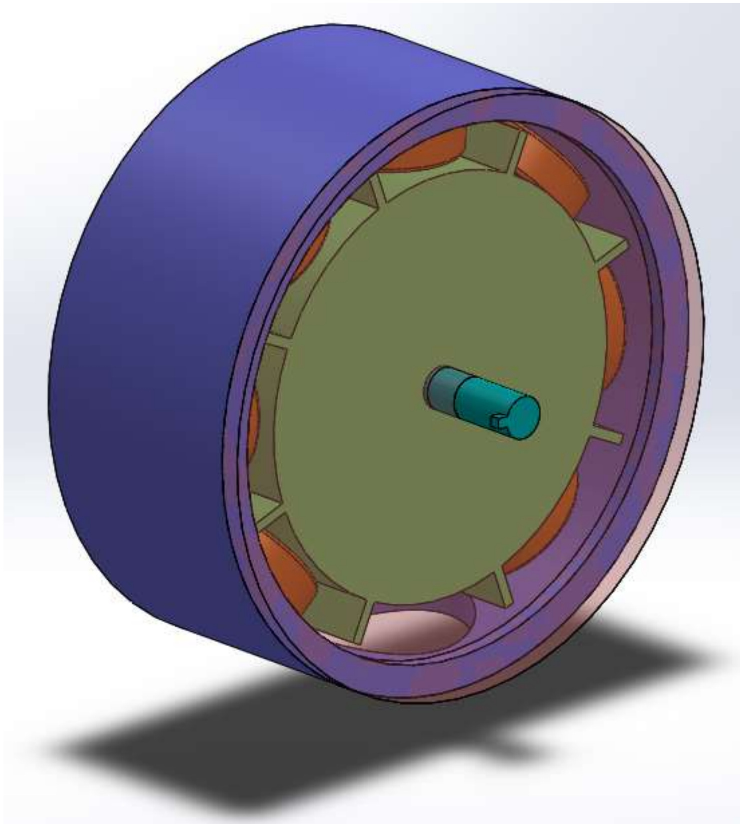

Figure 13. Design 6.

The “Turbo Puck Release,” named after its questionable similarity to an automotive turbo mechanism, was a modification of the turntable design. Pictured in Figure 13, the drum would be mounted sideways as opposed to vertically. The pucks would be indexed around an inner drum and would revolve around the central axis with the drums motion until they reached a drop hole on the lowest part of the drum. They would then be released from the mechanism. While this design boasted a combination of both storage and release in one component, the rotating drum would have to be large enough to fit an amount of pucks around its circumference to validate its use over other designs. Hence the design may be prohibitively large.

With proper positioning, this design would be capable of holding eight salt pucks, making it hold considerably more than other early designs. However, the outer diameter required to realize the potential would mean that the device was much larger than any other design. This device, at the time of its design, could only be reloaded through the release port on the bottom of the device; in retrospect, it could also be reloaded by removing one of the flat faces. The unorthodox design removed the risk of salt buildup from constant sliding friction between the faces of the salt pucks and the device’s components.

6.2.7 Design 7 - CD Changer

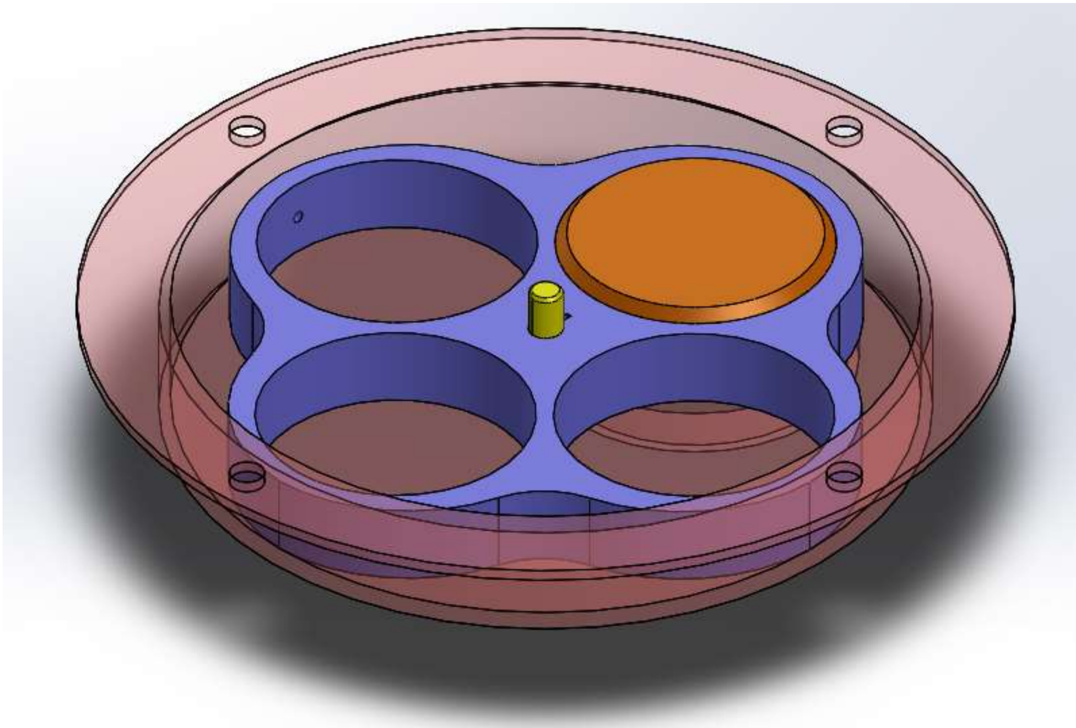

Figure 14. Design 7.

The “CD Changer” was designed to resemble the device from which it got its name: An older, large stereo system with capacity for multiple CDs. Here, salt pucks would take the place of CDs. This design could carry a maximum of four pucks and utilized a single moving component to achieve its motion. The CD Changer is similar in shape and concept to the previous two designs. This design focuses on being as simple as possible in order to complete the determined task. Pucks can be easily placed into the device from above, allowing for rapid reloading. While the device maintains sliding friction between the pucks and the bottom plate, the blue spinning component (“spinner”) in Figure 14 can be offset from the plate, thereby negating the risk of stalling the motor. The CD Changer also has a relatively well centered center of gravity when compared to other designs. This allows it to be mounted with little concern that it will cause the multirotor to tip over from the device’s weight. Along with its flat profile, the design would have a minimal effect on the flight of the multirotor.

The departure from vertical-tube-loaded mechanisms in these latter three designs came about largely due to manufacturability concerns and the fear of pucks falling prematurely. Upon preliminary research, tubes and the tube-plate interfaces of the necessary sizes could not be found. Such small-diameter tubes would render brackets infeasible (mounted using screws going through said tube) due to the screw head dimensions and curvature of the tube.

Pucks slipping out of the pre-drop position would be nearly impossible with this design, due to the presence of the tubular body and relatively small diameter of the drop hole (which pucks are often adjacent to). This design also retains the ability for a high capacity. In theory, the pucks could be stacked in layers, with a plate separating each layer. The limiting factors here would be the precision with which the spinners can be moved and the design of those separating plates, which are crucial to allowing second-layer pucks to fall down into the main first layer.

A derivative of this design ended up being the final prototype. This final design had two layers (and one separating plate) for a total capacity of seven pucks, in a more compact form-factor than the Turbo design.

6.2.8 Design 8 - Granular Funnel

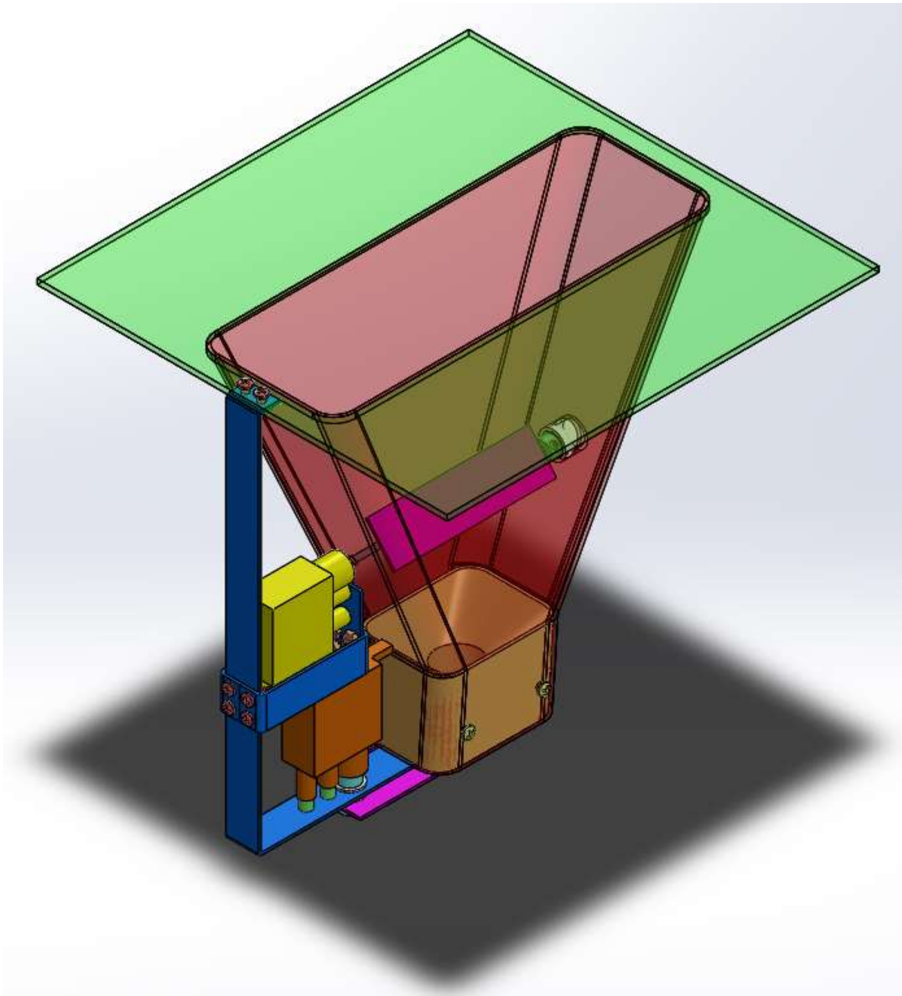

Figure 15. Design 8.

The “Granular Funnel” design was created to be exclusively for granular salt, as opposed to pucks, and features a completely different design than the others. It is also a much more refined and complete design, reflecting the fact that it is the most recent one. The original concept was to use a conventional funnel to both hold granular salt and guide it to a release hole. A gutter funnel forms the main body of the device. This funnel is the red, translucent piece in Figure 15.

The mechanism is made up of a large funnel that shrinks down via a diameter reducer to a small release “valve”. This valve is a rotating door controlled by a servo (shown as orange). Above the servo is a motor (yellow) that controls a rotating agitator. This component allows the user to remotely agitate the salt in the event of the salt clogging or otherwise getting stuck in the device. Due to the nature of granular salt, the only limitations on the carrying capacity of this design are the volume of the funnel and weight capacity of the multirotor.

The servo only needs to open and close a door, and the motor will only be used on the rare occasion that the granular salt gets clogged. As a result, power draw is low. This design is almost completely resistant to the effects of salt buildup as it is designed to pour out salt through the assistance of gravity. Any considerable salt buildup will be flushed out of the release valve along with the granular salt. Given its simplicity, this design is highly desirable as a means to drop granular salt, and no further iteration took place on this front.

Originally, one design that incorporated the ability to drop both forms of salt (pucks and granular) was sought. It was determined that more salt could be carried while still meeting the functional specifications by making this separate mechanism. The separate mechanisms would be rapidly interchangeable instead.

6.2 Weighted Design Matrix

The designs were compared using a set of five weighted criteria. These criteria are as follows:

- Mass: Weight 0.30
    - Mass is critical in determining whether or not the design can be feasibly carried by a multirotor and as such, is the most restrictive element on the table.
    - Scoring:
        - 1: Design has a mass of over approx. 2kg
        - 2: Design has a mass between approx. 1.0kg and 2kg
        - 3: Design has mass below approx. 1kg
- Payload: Weight 0.25
    - Payload refers to the amount of pucks or granular salt that can be carried by the design before needing to land and reload.
    - Scoring:
        - 1: Design can carry 3 or fewer pucks / equivalent granular salt
        - 2: Design can carry 3 to 5 pucks / equivalent granular salt
        - 3: Design can carry 6 or more pucks / equivalent granular salt
- Manufacturability: Weighting 0.20
    - Manufacturability refers to the ease with which the design can be manufactured. Overly complex designs may function better or be more optimized, but they may not be able to be repaired quickly and easily should the multirotor crash.
    - Scoring:

        - 1: Many components must be manufactured elsewhere, take a long time to do so, or are difficult to assemble
        - 2: Some components must be manufactured elsewhere, take a moderate amount of time to do so, or are moderately difficult to assemble
        - 3: Most components can be manufactured without outside aid, take a low amount of time to do so, or are easy to assemble
- Modularity: Weighting 0.10
    - Modularity is a term used to describe the ease with which the devices can be broken down or slightly modified to accommodate different salt payloads (puck form versus granular form), in order to be repaired or to provide flexibility. An emphasis is placed on the ability of the device to be broken down for repair, as the plan is to make two separate mechanisms for different salt formats.
    - Scoring:
        - 1: Design cannot be modified for different types of salt / cannot be broken down
        - 2: Design may be able to accommodate different types of salt with some difficulty / can be broken down with some difficulty
        - 3: Design requires no refitting to accommodate different types of salt / can be broken down easily
- Simplicity: Weighting 0.15
    - Simplicity categorizes designs with fewer moving parts as simpler. Fewer moving parts results in fewer potential failure points, and fewer locations at which salt may jam the mechanism.
    - Scoring:
        - 1: Design has 4 or more moving parts
        - 2: Design has 2 to 3 moving parts
        - 3: Design has 1 moving parts

Table 1. Weighted Design Matrix for the Preliminary Designs.

	Mass	Payload	Manufacturability	Modularity	Simplicity	RANK
Weighting	**0.30**	**0.25**	**0.20**	**0.10**	**0.15**	**1.00**
Vertical Tube with Shelves	3 (0.9)	2 (0.5)	1 (0.2)	1 (0.1)	2 (0.3)	2.0
Crank-Slider	3 (0.9)	2 (0.5)	3 (0.6)	3 (0.3)	2 (0.3)	2.6
Turntable	2 (0.6)	2 (0.5)	2 (0.4)	2 (0.2)	2 (0.3)	2.0
Rack and Pinion	2 (0.6)	2 (0.5)	2 (0.4)	3 (0.3)	1 (0.15)	1.95
Turbo Puck Release	1 (0.3)	3 (0.75)	2 (0.4)	1 (0.1)	3 (0.45)	2.0
Swivel Arm	3 (0.9)	2 (0.5)	3 (0.6)	2 (0.2)	2 (0.3)	2.5
CD Changer	3 (0.9)	2 (0.5)	3 (0.6)	2 (0.2)	3 (0.45)	2.65

Based on the design matrix shown in Table 1, the best design is the CD Changer. This design is comparatively light and easy to manufacture using rapid prototyping methods such as laser cutting. While it does not have the highest capacity, it could potentially be used to hold granular salt (by replacing the puck holes with vertical tubes of salt, for example). The CD Changer was chosen to be developed further.

In addition to the CD Changer, the lone granular mechanism was also deemed feasible. Although it cannot dispense salt pucks, it specifically answers the problem of how to hold and release granular salt for whatever applications may be deemed beneficial to do so. The decision to proceed with two designs allowed for more specialization for either form of salt. Modularity has a low weighting because this development was predicted.

7.0 Selection of Final Designs

Upon careful analysis of the preliminary designs and review of the weighted design matrix, the CD Changer and Granular Funnel designs were selected for final design iteration. For the sake of being able to transition between deploying deicing pucks and granular salt as quickly as possible, a modular system that divided the two operations between two separate mechanisms would be ideal.

7.1 Constraints

The DJI S900 multirotor allows an approximate 2.5kg payload. Measurements of interest with this multirotor in mind are shown in Figure 16.

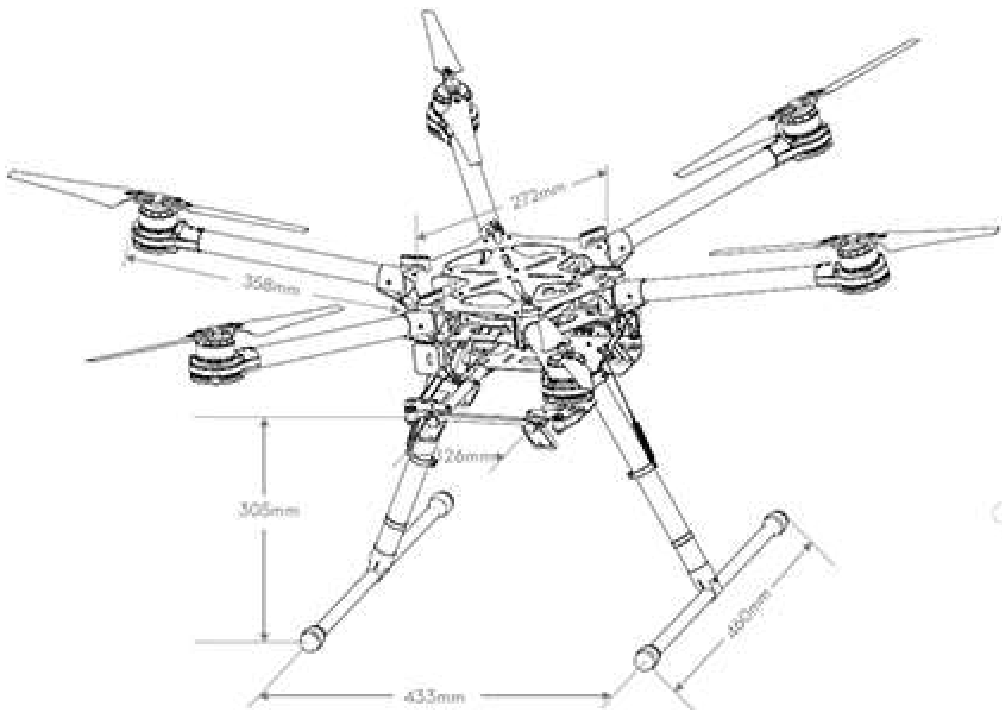

Figure 16. DJI S900 Dimensions. [48]

Based on Figure 16, each of the mechanisms could be no higher than 280mm, or approximately 11in, based on the 305mm height dimension and allowing a 25mm tolerance (approximately 1in).

The depth dimension was not of large concern (parallel to the ground-contacting portions of the landing gear in Figure 16). The mechanisms may be arbitrarily long along that dimension, provided the center of mass is vertically in-line with that of the multirotor. An ideal center of mass would remain on the plane formed by the roll and yaw axes, below that of the multirotor. Maintaining a center of mass in this manner avoids movement along the pitch axis (and consequently, rotation about the roll axis), which is critical for allowing careful, precise operation and stability of the multirotor. Very minor movement along the roll axis (forward/back on the multirotor) may be corrected for by the flight controller of the multirotor and is therefore acceptable, but should be minimized as much as possible.

See Figure 17 for a graphic of the pitch, roll, and yaw axes of a multirotor. To clarify between Figures 16 and Figure 17, the roll axis is parallel to the 460mm length dimension (in the multirotor forward/backward direction), the yaw axis is parallel to the 305mm height dimension (multirotor up/down direction), and the pitch axis is parallel to the 433mm width dimension (multirotor left/right translation).

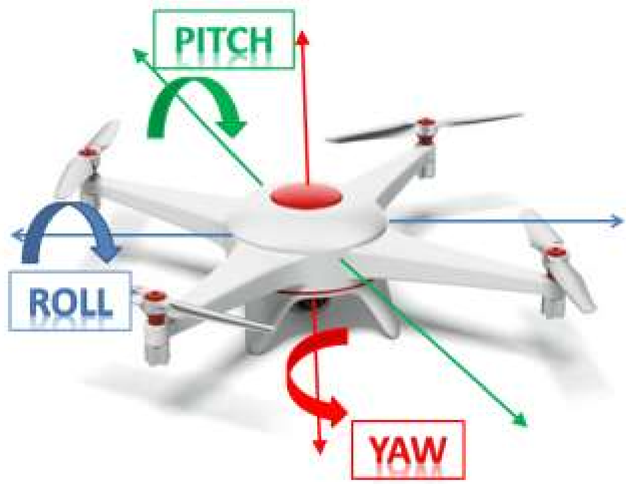

Figure 17. Roll (FWD/BACK), Pitch (LEFT/RIGHT), and Yaw (UP/DOWN) axes. [49]

As previously discussed, the S900 and the S1000+ multirotor models have a largely identical gimbal mounting situation, between the ground and the center of the frame, between the landing gear legs. Physical access to the S1000+ model allowed for closer inspection. There are four mounting brackets forming a rectangular area, shown in Figure 18. These brackets are intended to interface with camera gimbal equipment, but they could also function as custom mounting hard-points. The brackets can slide in the forward/back direction of the multirotor to promote optimal center-of-mass placement. Each one contains two threaded holes for M2.5 screws. One such bracket is shown in Figure 19.

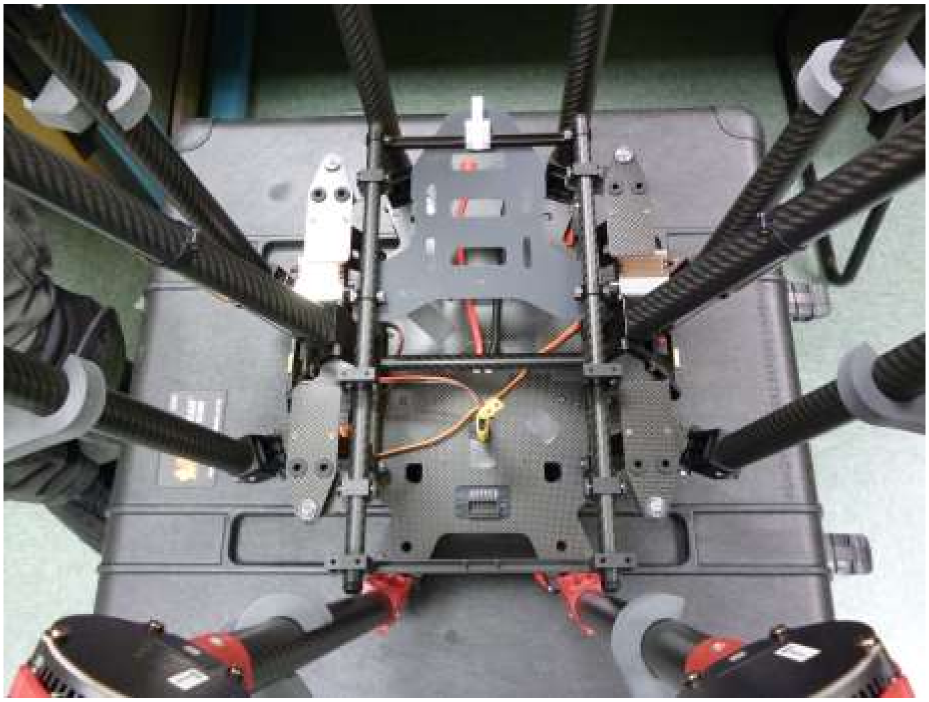

Figure 18. DJI S1000+ bottom view.

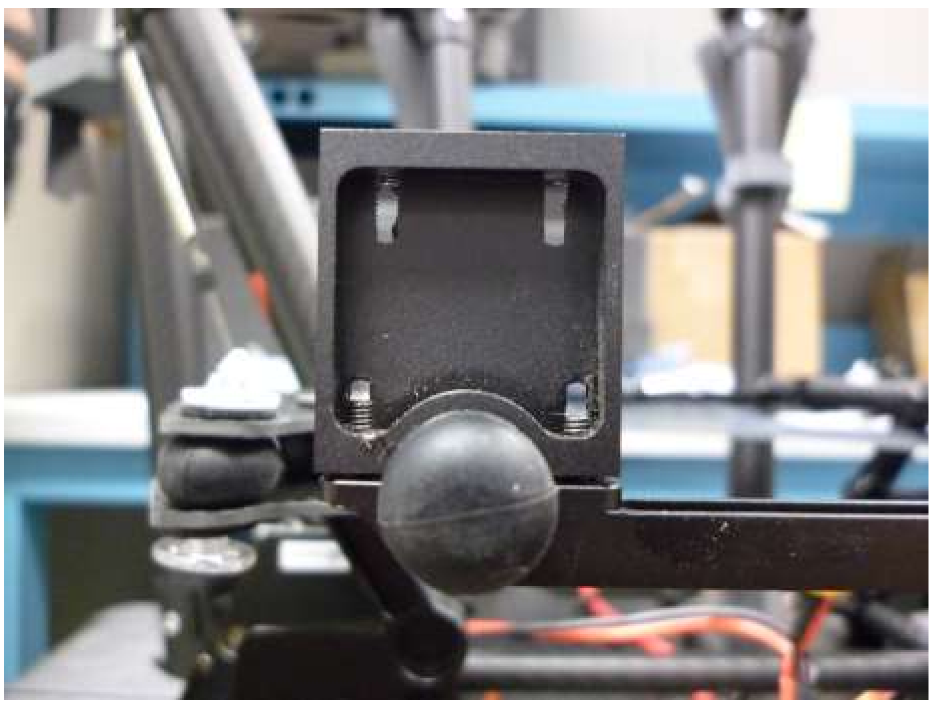

Figure 19. One mounting bracket on the bottom of the DJI S1000+.

The bars upon which these brackets slide is 12mm in diameter. These bars are 329.5mm long (not including the capped ends). 40.5mm from each bar's end is a static, 10mm wide structural member (the other end of which sits 50.5mm from the bar's end). The inside edges of the brackets are fixed approximately 130mm apart, but they can slide along the bars (excluding where the structural members reside). The brackets themselves are approximately 14mm wide each, in the multirotor left/right direction. They are 8mm thick (along the direction they can slide).

There is a minimum 8.5in of horizontal (multirotor left/right) space between the multirotor's retractable, upside-down-T-shaped landing legs at the bottom of the gimbal mounting brackets. In practice, this means the mechanisms cannot be over 8.5in wide at any point that places them between the landing legs. With the landing legs extended, there is 12in (30.5cm) of space between the brackets and the ground, meaning that the mechanisms cannot exceed 12in of height below the mounting points. Recall that the S900 has a constraint of 11in.

The exact dimensions of interest for the S1000+ are shown visually in a user manual for the multirotor. This is shown in Figure 20.

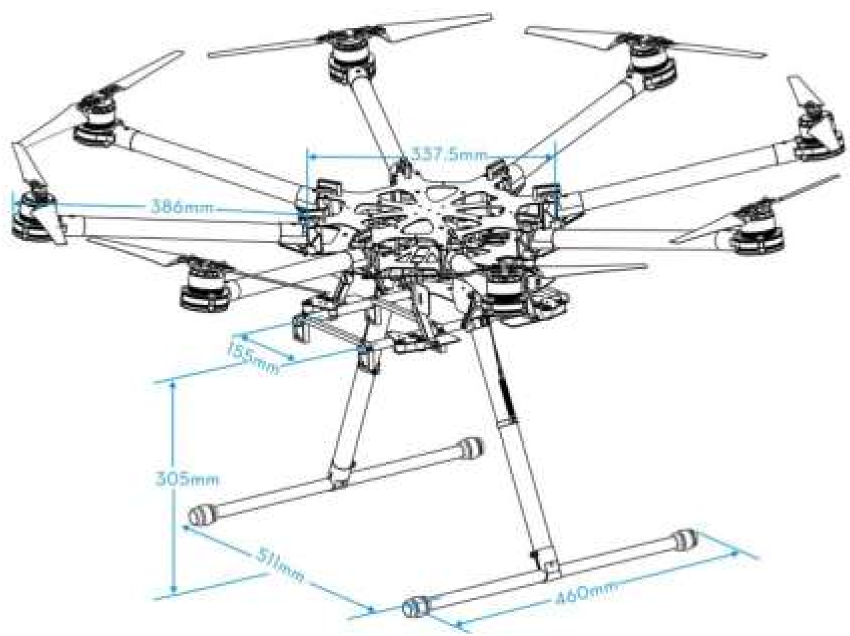

Figure 20. DJI S1000+ Dimensions. [50]

7.2 Selection of Materials and Fasteners

7.2.1 Material Selection

A successful design minimizes mechanism mass and maximizes salt payload mass. With this in mind, lightweight and corrosion-resistant materials were sought, while also considering cost and availability.

Acrylic, polycarbonate, vinyl, and PLA (3D-printed material) are all lightweight and easy to shape via rapid prototyping or hand-tooling methods. Aluminum was selected as a reference material seeing as it is the most cost-effective, commonly-used lightweight metal material, especially for aerospace applications that do not instead use expensive composites. Table 2 shows that the densities of these plastic materials are all less than that of Aluminum [51][52], resulting in weight savings. For the few parts requiring more intensive machining, Aluminum would be used sparingly.

Table 2. Material Properties.

Material	**Density (g/cm^3)**
Acrylic	1.19
Polycarbonate	1.53
Vinyl	1.4
Polylactic Acid (PLA)	1.25
Aluminum	2.7

Acrylic is easy to work with and readily available due to its ability to be laser-cut. Polycarbonate cannot be laser cut due to the toxic fumes that result, so it would be used for parts requiring little machining. It is known for its impact-resistant properties, making it ideal for protective applications for one or both of the mechanisms [53]. Vinyl is available in many pre-formed shapes, e.g. for gutter systems, which could be used as a base for one or both designs.

7.2.2 Rapid Prototyping

Acrylic can be laser cut, which is an extremely fast and accurate process to manufacture flat parts. The desired face of a flat SolidWorks model can be exported as a *.DXF file for use in AutoCAD. When converted to a *.DWG file, colored in the scheme that the cutter recognizes, and plotted (like a conventional printer), very rapid prototyping is achieved. The relevant colors that the cutter recognizes are red (cut) and blue (engrave). A maximum 18” x 24” Continuous Cast Acrylic sheet can fit in the bed of the VersaLaser cutter in the Washburn Shops at WPI.

PLA (Polylactic acid) is a common material used in 3D printing. 3D printing allows for complex, lightweight 3D parts. The MakerBot Replicator 2 in the Undergraduate Robotics Laboratory in Atwater Kent has a small bed capable of printing parts up to 11.2 x 6.0 x 6.1 inches [54]. It uses heated extrusion to melt and place PLA layer-by-layer until the part is complete. At a cost of approximately $0.10/gram, this is a very economical way of rapidly making parts that have non-uniform or unconventional shapes. The only input needed is an *.STL file of the part to be printed, which SolidWorks is capable of producing.

Whenever possible, rapidly-prototyped pieces incorporated fillets to reduce stress concentrations induced by fasteners and other loads. Doing so requires no special machining or part modification, due to the ease with which such parts may be manufactured.

7.2.3 Fastener Selection

We selected fasteners that were composed of either Type 306 or Type 304 (also known as 18-8) stainless steel due to its light weight and corrosion resistance, particularly to saltwater [55]. Screw sizes were determined by constraints introduced by other components (e.g. the motors required #6-32 screws, and large through-holes required larger head sizes).

Philips pan-head screws were selected due to their form factor and high tool availability. Hex key screws were considered, but prior experience with stripping and the need for easily-lost keys led to this idea being rejected.

7.3 Inclusion of Motors and Electronic Components

The puck mechanism would require one motor, and the granular mechanism would require one motor and one servomotor. The specific functions of these motors will be discussed later on in the two respective final mechanism design sections of the report.

Per advice given from Joseph St. Germain (in the WPI Robotics Engineering Department), separation of the mechanism power and control from the multirotor’s electronics would be ideal. Each mechanism would require a battery, receiver (on a different band from the multirotor control receiver), and ground controller/transmitter configuration, referred to collectively as the “driving electronics.” For the two mechanisms and their respective motors, it would be possible to use a single battery pack, receiver, and common ground controller/transmitter to control the motors, switching the connections as necessary.

The factor of safety described in Sections 3.3.3 and 3.3.4 (the total payload capacity minus 1kg) was designed with the intent of capturing all of the extra mass of the required driving components - including what the multirotor needs to function as well as whatever additional electronic components are needed to drive the mechanisms. These driving electronics were predicted to be of sufficiently low mass to be included in this 1kg factor of safety.

7.4 Mounting Mechanisms to the Multirotor

7.4.1 Design of the Multirotor Mounting Units

Four separate and identical mounting tabs were designed to reduce size and weight, one for each of the multirotor’s four mounting brackets. Each mounting tab would contain two M2.5 clearance holes to interface with the multirotor gimbal mounts (using 12mm-long 18-8 stainless steel screws), as well as one clevis pin hole. The later would serve to secure each mechanism to the four mounting tabs in an easily-removable fashion. One of the four mounting tabs is shown in Figure 21.

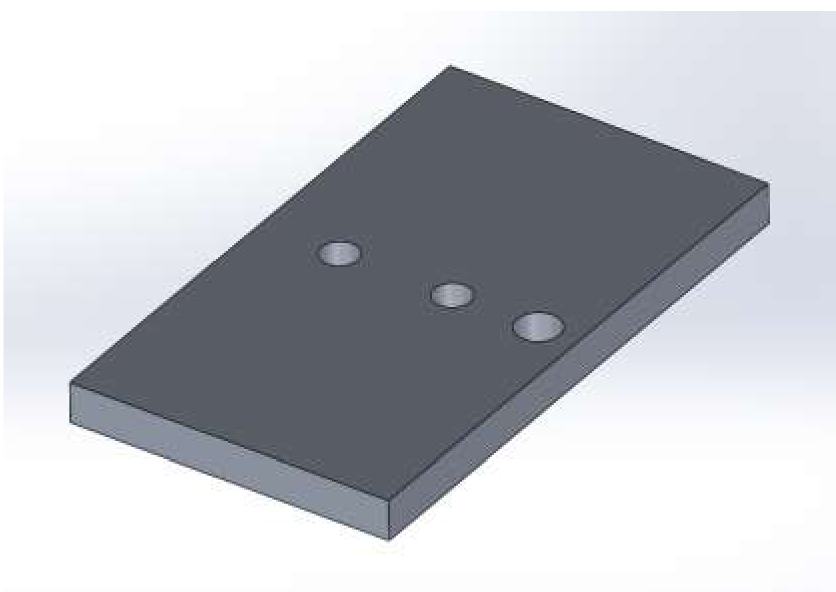

Figure 21. One of the four mounting tabs.

The material chosen was 0.125”-thick 6061 Aluminum. These are load-bearing components that must not fail, hence the departure from a plastic alternative. The thickness was chosen to minimize bending and weight while not sacrificing structural integrity. 6061 Aluminum is lightweight, highly machinable, and corrosion resistant. A Finite Element Analysis discussed in Section 7.4.3 proves the viability of this choice. SolidWorks Mass Properties was used to determine the total mass of the four 1in x 2in mount tabs as 0.03796kg.

7.4.2 Design of the Generic Rectangular Mounting Plate

In order to interface with the mount tabs, each mechanism would need a plate containing four clevis pin holes and enough material to be supported by the aluminum tabs. Such a design would prevent any lateral or vertical motion from unseating the mechanism (with the addition of a cotter pin inserted into each clevis pin).

The dimensions of the generic mounting plate were minimized at 10.5in x 5.0625in while bearing the previous constraints in mind. Each of these rectangular mounting plates would be customized in order to support each mechanism. Acrylic’s ease of customization via laser cutting led to 0.125” thick Acrylic as the material choice. A generic, rectangular mounting plate can be seen in Figure 22.

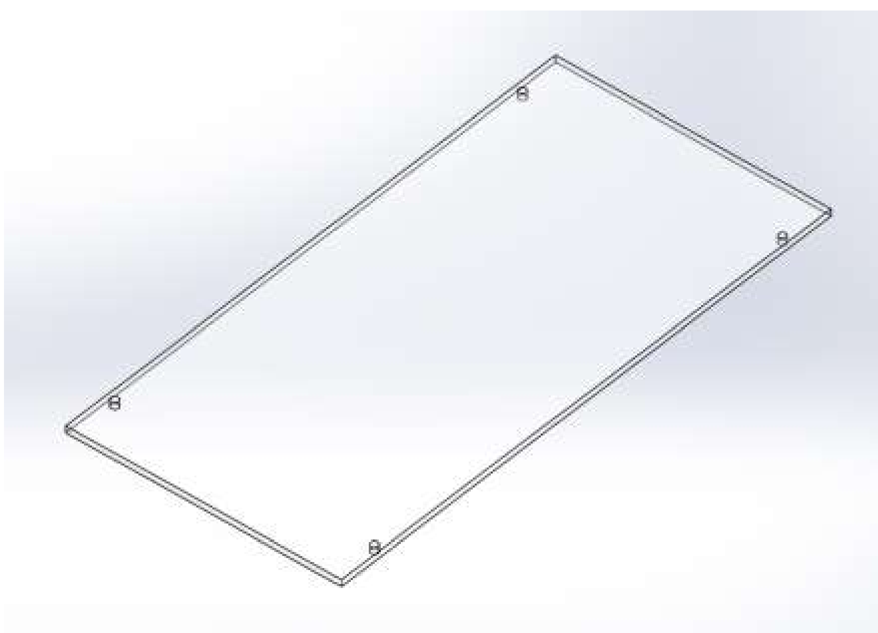

Figure 22. Uncustomized rectangular mounting plate template, used by both mechanisms.

A Finite Element Analysis discussed in Section 7.6.6 proves the viability of this choice, using the structurally weaker of the two customized mounting plates (the granular deployment mechanism plate). SolidWorks Mass Properties was used to determine the mass of one generic mount plate as 0.13052kg.

Figure 23 shows how the multirotor mounting tabs and plate interact, and how the mounting tabs connect to the multirotor brackets. The blue portion of the assembly is a model of the multirotor gimbal mounting apparatus, to which the mounting tabs attach via the M2.5 screws.

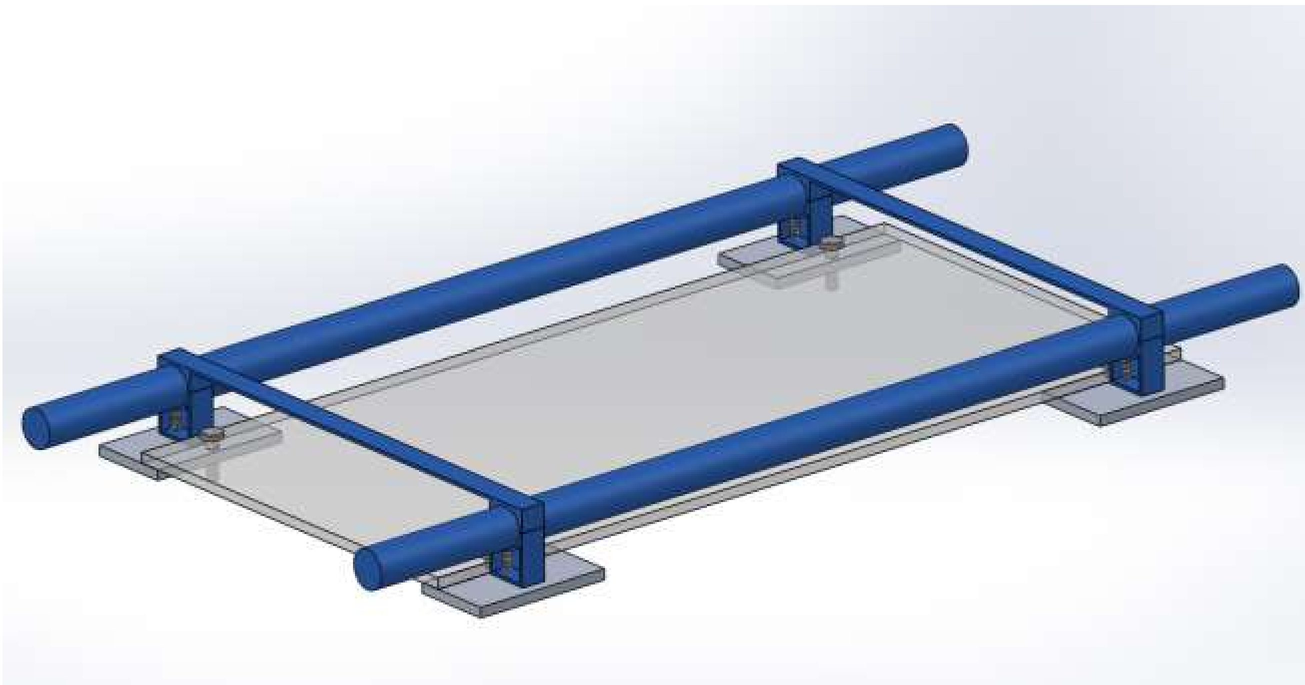

Figure 23. Rectangular mount plate, as it interfaces with the mounting tabs and S1000+ gimbal mounting brackets.

7.4.3 Finite Element Analysis of the Mounting Units

To ensure the integrity of the aluminum mount tabs, a Finite Element Analysis was run using SolidWorks SimulationXpress. A maximum payload of 2.5kg results in 0.625kg of supported mass per mounting tab. A factor of safety of three was employed, for a conservative total of 1.875kg supported mass per mounting tab.

In the SolidWorks simulation, the mounting tab was fixtured in the area where it comes in contact with the multirotor-side mounting bracket, and in the areas where the screw heads contact the underside of the mounting tab. An equivalent force of 18.39375N (the effect of gravity on the 1.875kg payload) was applied over the area where the surface of the multirotor-side mounting bracket comes in contact with the mounting tab to simulate the potential weight of each of the mechanisms. In Figure 24, the top two views show the fixtured areas, and the bottom view shows the area where the forces were applied.

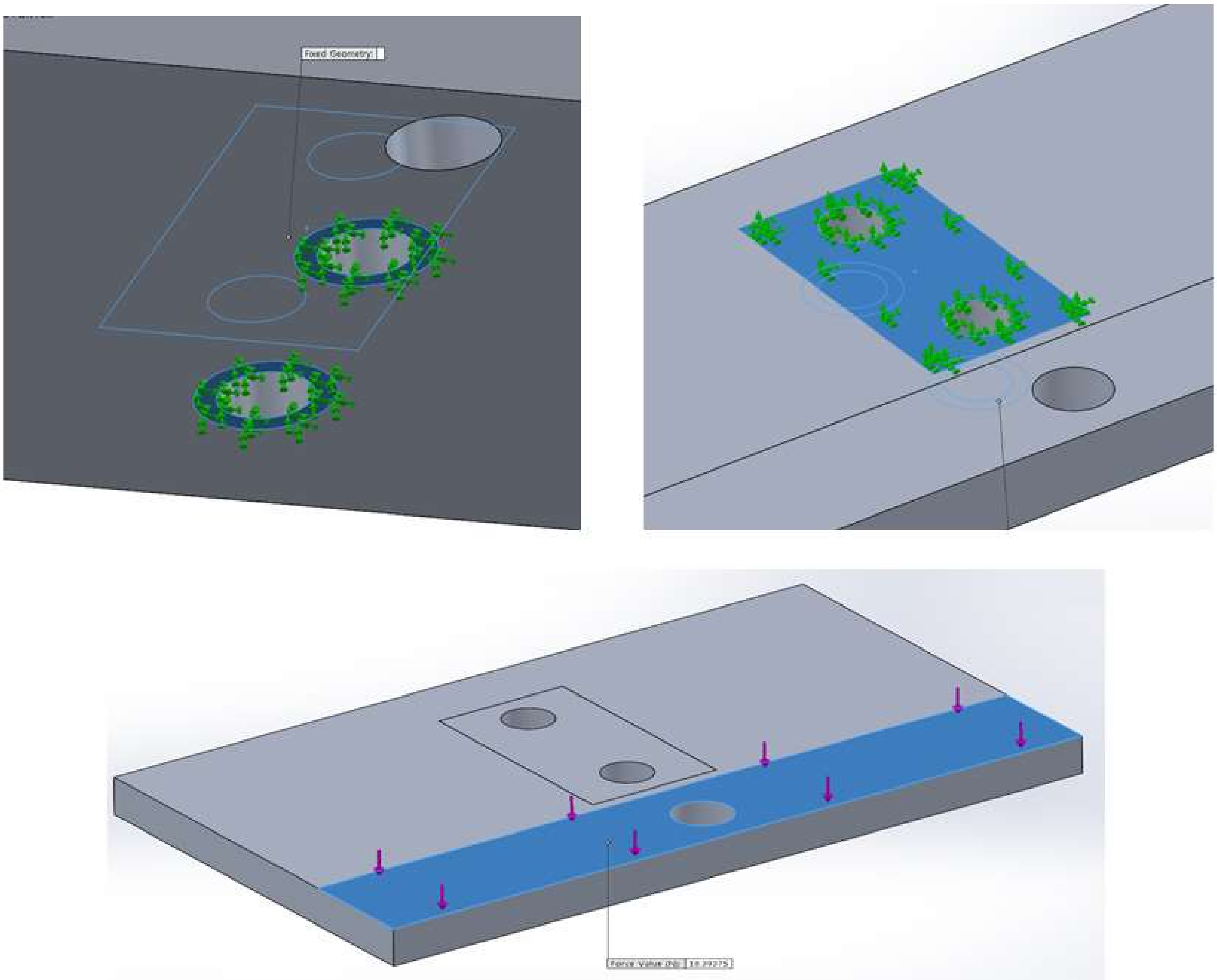

Figure 24. Mounting tab Finite Element Analysis.

Analysis shows that the mounting unit deforms a maximum of 0.003047mm (0.00012in), and experiences a maximum von Mises stress of $7.054*10^6 N/m^2$. Aluminum's yield strength of $2.5*10^8 N/m^2$ means the mounting tab design will not fail under the stated maximum von Mises stress. Figures 25 and 26 show the results of the von Mises stress and deformation analyses, respectively.

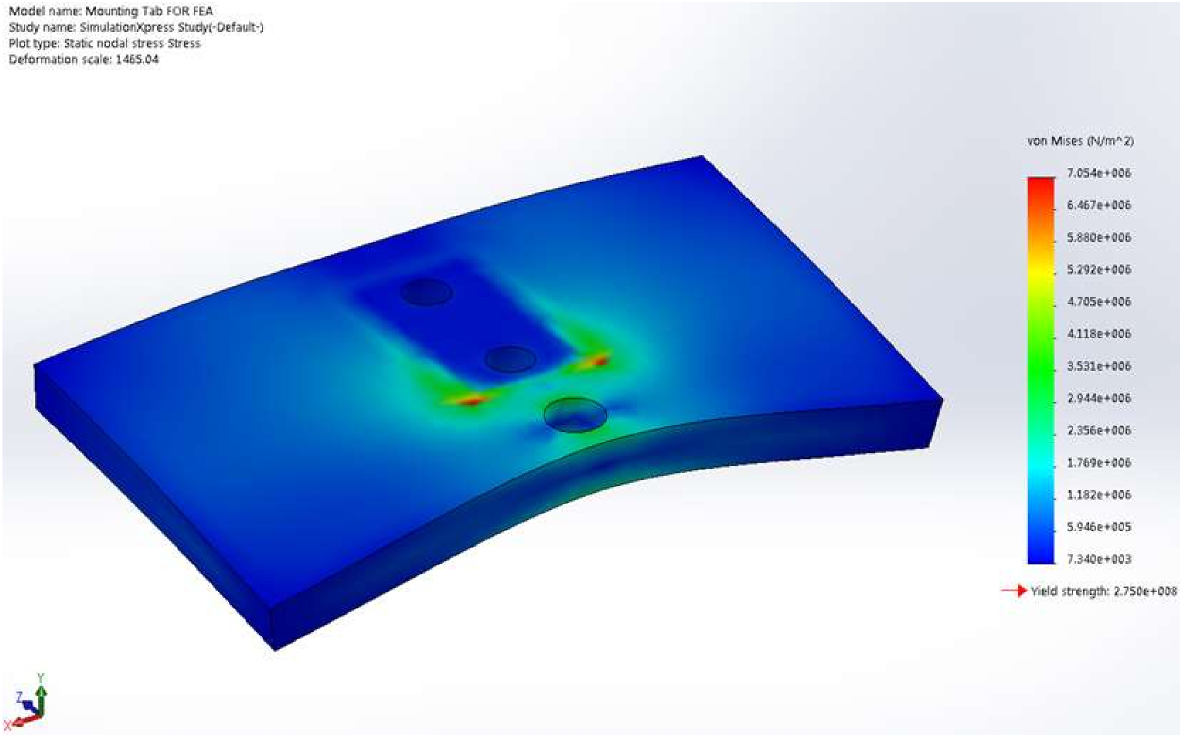

Figure 25. Mounting tab von Mises stress analysis.

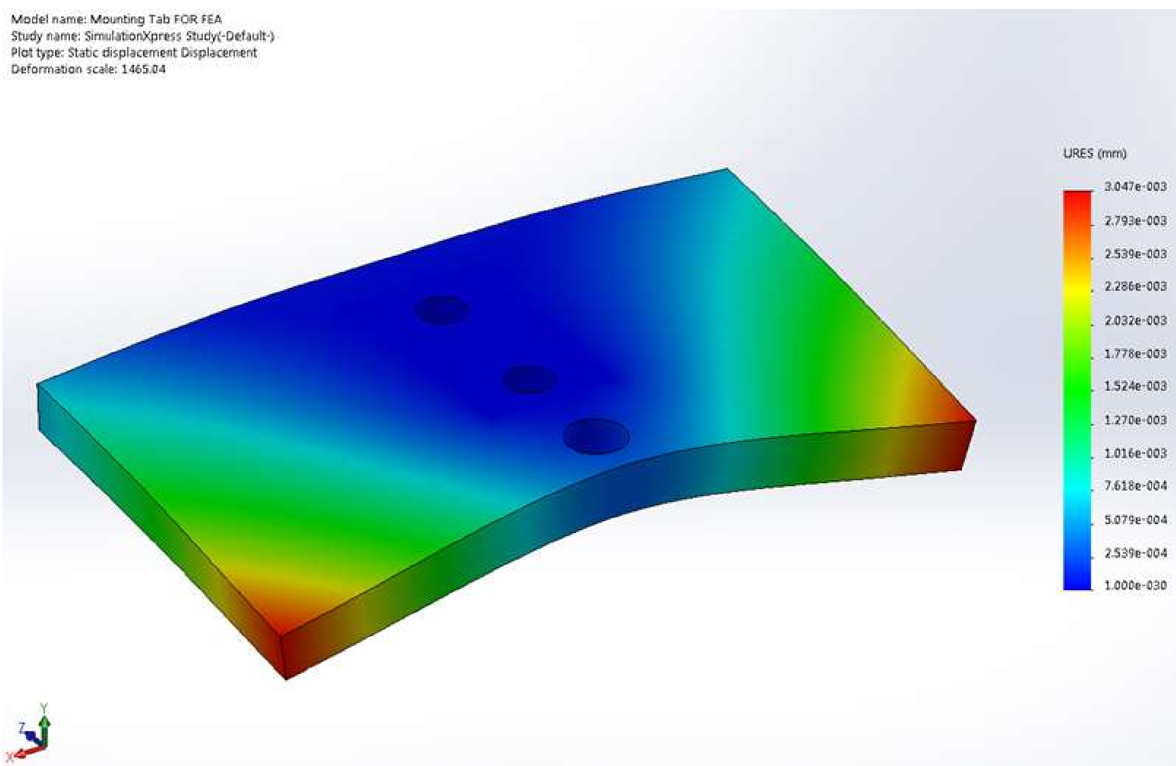

Figure 26. Mounting tab deformation analysis.

7.5 Development of the Puck Mechanism Final Design

7.5.1 General Description of Purpose

The Puck Mechanism, based off the "CD Changer" design, is designed to drop 2.5in wide Roofmelt ice pucks onto winter roofs behind ice dams. This is an alternative to throwing the pucks (the conventional way), allowing for much greater precision in their dropping, even if simply relying on line-of-sight operation.

7.5.2 Determining a Mass Limit for the Mechanism

Table 3 shows the calculation of an average Roofmelt ice puck mass, for use in determining the puck deployment mechanism mass.

Table 3. Roofmelt salt puck mass and dimension measurements.

Sample	Mass (kg)	Height (in.)	Diameter (in.)
1	0.101	1	2.25
2	0.109	1	2.25
3	0.103	1	2.25
4	0.099	1	2.25
5	0.101	1	2.25
6	0.103	1	2.25
7	0.100	1	2.25
8	0.102	1	2.25
9	0.101	1	2.25
10	0.101	1	2.25
Average	**0.102**	**1**	**2.25**

Using this data, a puck mass of 0.1 kg was used for further calculations, with the extra 0.002kg difference from the average mass reconciled by variation in puck size and shedding of material during handling. Each has a height of 1 in and a diameter of 2.25 in. The small ice puck height made multiple layers (and more puck capacity) an option. Thus, seven pucks could be carried total. Four pucks on the bottom level and three on the second level would require minimal modification of the preliminary design. It would be necessary to carry three pucks instead of four on the second level to facilitate smooth transitioning of these pucks to the first level; this aspect of the design will be discussed later.

Seven pucks have a mass of 0.7kg, and the total payload capacity of 2.5kg results in a maximum empty mechanism mass of 1.8kg. Efforts were taken to reduce the actual prototype mass below this value.

7.5.3 Design Development/Construction

In a choice between readily-available 0.625in, 0.125in, and 0.25in-thick material, the 0.125in thick material offers an optimal balance between structural integrity and low total mass. Mass-saving measures were employed in parts for which the additional material offers no meaningful structural benefit. A combination of acrylic parts and laser cutting would make manufacturing of the resulting complex shapes very simple.

The bottom and middle plates of the puck deployment mechanism serve as the traveling surfaces for their respective puck layers; the bottom plate serves the first layer of pucks, and the middle plate serves the second layer. These are shown in Figures 27 and 28, respectively. By creating a series of cutouts in these parts and thereby removing material, the surface area over which the pucks come in contact with the plates are reduced. Lower mass and puck-plate friction result. The orientation of these slot-shaped cutouts is of interest as well. If oriented radially from the center, such cutouts would cause many straight sharp edges on which the pucks may catch. Oriented along the path of motion of the pucks, the slots only present small obstacles to the pucks at their rounded ends.

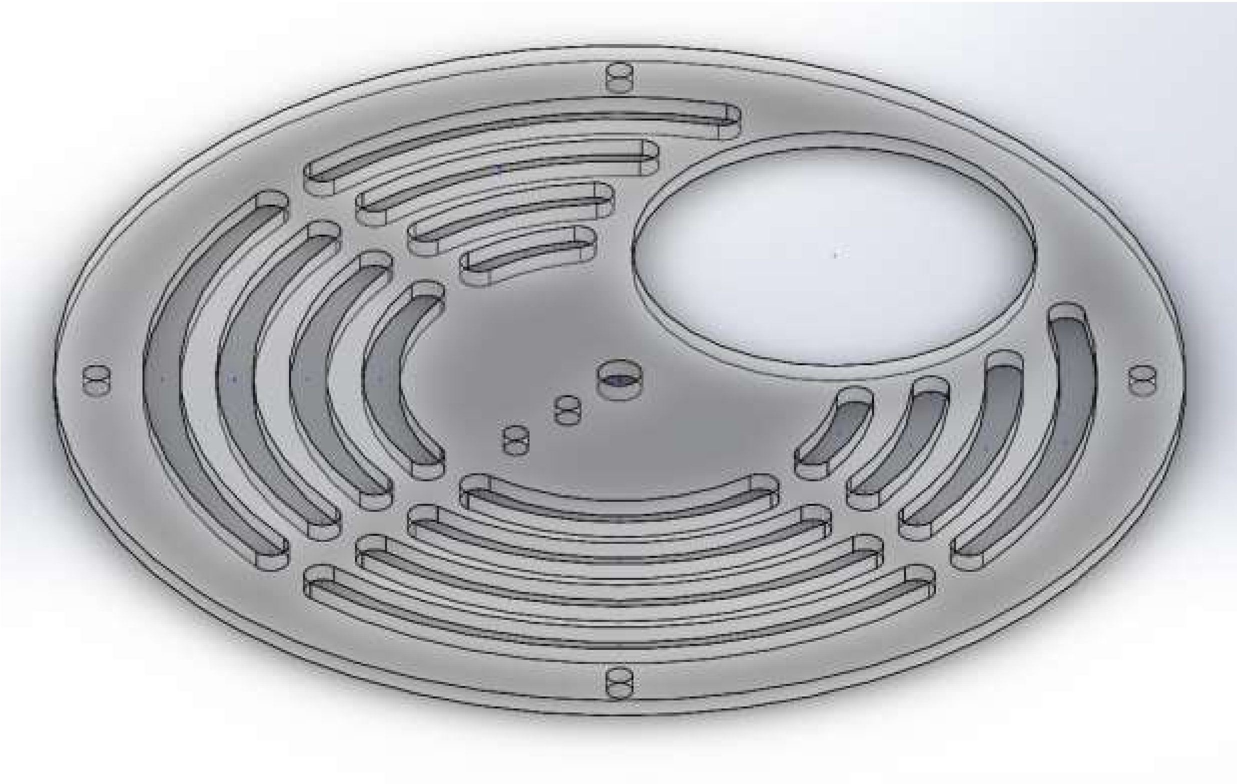

Figure 27. First-layer plate, with drop hole leading out of the mechanism.

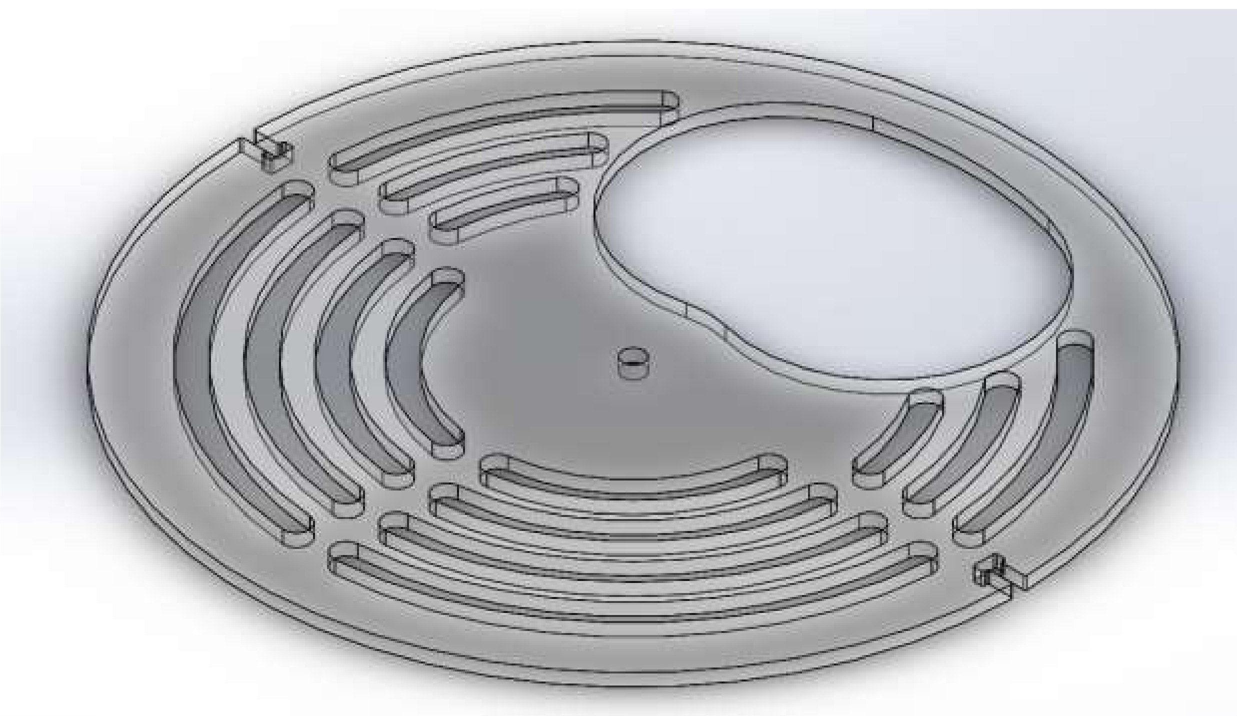

Figure 28. Second-layer plate, with drop hole leading to the first layer of the mechanism.

The two spinners come in direct contact with the pucks and are responsible for moving them, ultimately cycling each puck to the puck deployment hole. In order to minimize the material used for these components, a simple circular outer diameter was replaced with a leaner weight-saving curved design, as seen in Figure 29.

The first and second-layer spinners were oriented at a slight angle to each other (approximately 2.5 degrees). This was the result of many iterations and a sizeable amount of acrylic sheet. Feasibility testing during the build phase demonstrated that the second-layer pucks would often fall onto the first-layer spinner, rather than into its vacant puck receptor. It was hypothesized that this was caused by a combination of difficulty in controlling tolerances and a reduced force upon the second spinner (only three pucks' worth of friction on the second layer as opposed to four on the first layer, initially). A small angle offset would result in the second-layer pucks not falling onto the first-layer spinner any longer. The Load and Drop testing would see this in action.

Figure 29. A spinner, with four puck acceptor holes.

Seven pucks were implemented in this design instead of eight due to the jamming that would result between the first and second layers with its inclusion. A plate holding the eighth puck and a rotating arm above the second layer could be used to rectify this, but a small angle of 17.74 degrees tilt would destabilize this puck. The shelf was still designed and implemented, with the alternative application of keeping pucks from tilting and jamming the mechanism while falling from the second to first layer.

One more key consideration that was kept in mind while developing the final puck mechanism was maintaining a center of mass along the plane formed by the multirotors roll and yaw axes, as discussed in Section 7.1 of the report. This would ensure stable operation of the multirotor as it transports pucks up to the ice dam. To achieve this, the mechanism was developed to be symmetrical about this plane. Relevant calculations are reported further on in the report with regards to the shifting of the center of mass as pucks cycle through the device.

An exploded view of the entire assembly is shown in Figure 30. In order, the parts are:

1. Top plate, used to stop pucks from tilting as they fall from the second to first layer
2. Second-layer salt pucks x3
3. Second-layer spinner
4. Second-layer plate (middle plate) with drop hole to first layer
5. First-layer salt pucks x4
6. First-layer spinner
7. First-layer plate (bottom plate) with drop hole to roof
8. Axle
9. Mechanism shell
10. Motor clutch, to prevent breaking the motor under high-torque conditions
11. Motor (VEX 393)

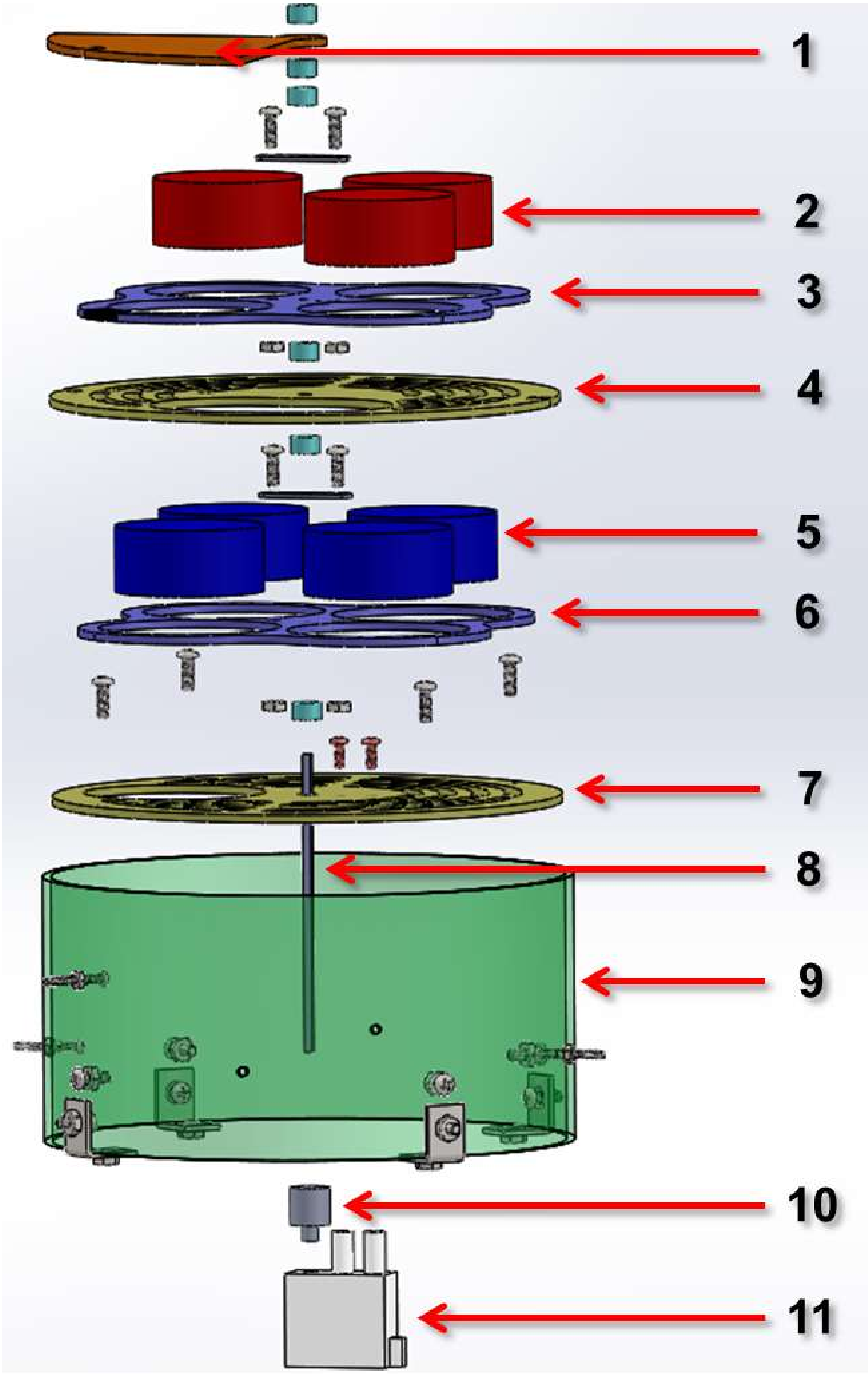

Figure 30. Puck mechanism exploded view.

The mechanism is entirely controlled by a single motor (shown in white, part 11) mounted to the bottom of the first-layer plate (7). This motor is connected directly to a shaft (8) that rotates both spinners (6 and 3). The spinners themselves are aligned at a slight angle with each other to allow the pucks sitting on the second-layer plate (4) to fall directly into the lower spinner, without landing on the lower spinner itself. All of the components around the central square shaft are kept in place with a series of collars (colored cyan). The shaft is kept vertically aligned by square holes cut into the mounting plate and the electronics plate (not shown).

The assembly process for the Puck Mechanism is relatively straightforward. First, the first-layer plate (7) is affixed to the body tube (9) by using the type 1 (7/8" x 7/8") brackets and 8-32 screws. The motor (11) and a matching clutch to prevent motor damage (10) are then mounted to the first-layer plate using size 6-32 screws. After this, more 6-32 screws are used to create a "shelf" to rest the second-layer plate (4) on. Shaft collars are used to separate and position the spinners and top plate. Components are placed on the shaft in the following order: Collar, bottom spinner (6), collar, second-layer plate (4), collar, second-layer spinner (3), collar, collar, top plate (1), and collar. The second-layer and top plates, in addition to the 6-32 screws and collars, use 4-40 screws to lock them in place. Lastly, type 2 brackets (1" x 1") are affixed to the top of the body tube using 8-32 screws. These brackets are not shown in Section 7.5.5, but are around the top edge of the green drum shown in Figure 31.

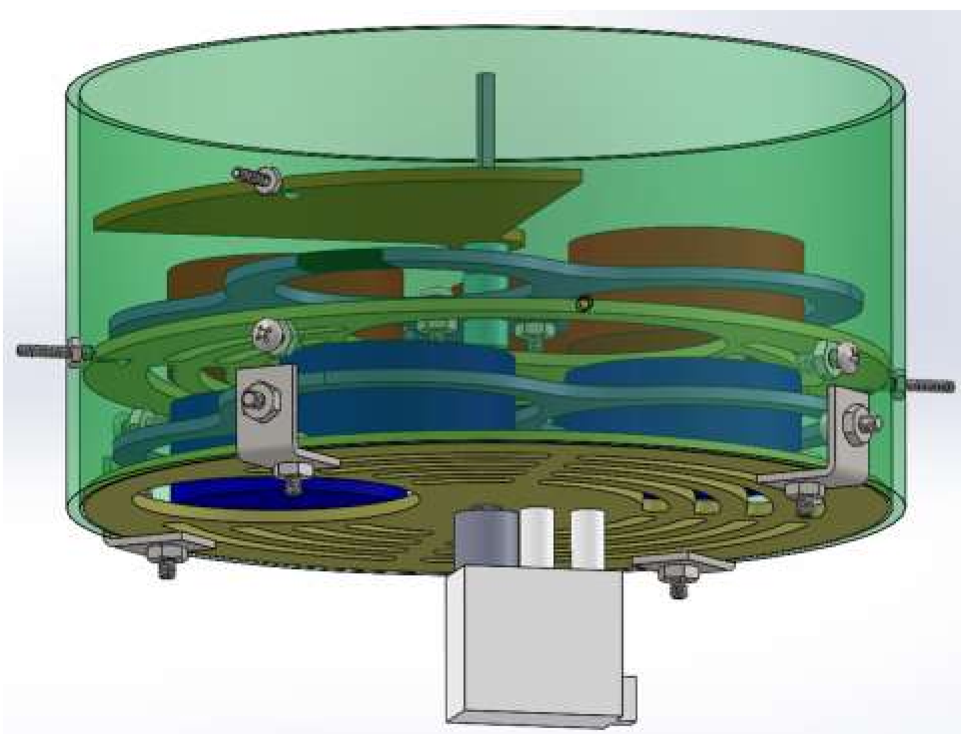

Figure 31. Puck mechanism main body assembly.

7.5.4 How the Puck Mechanism Works

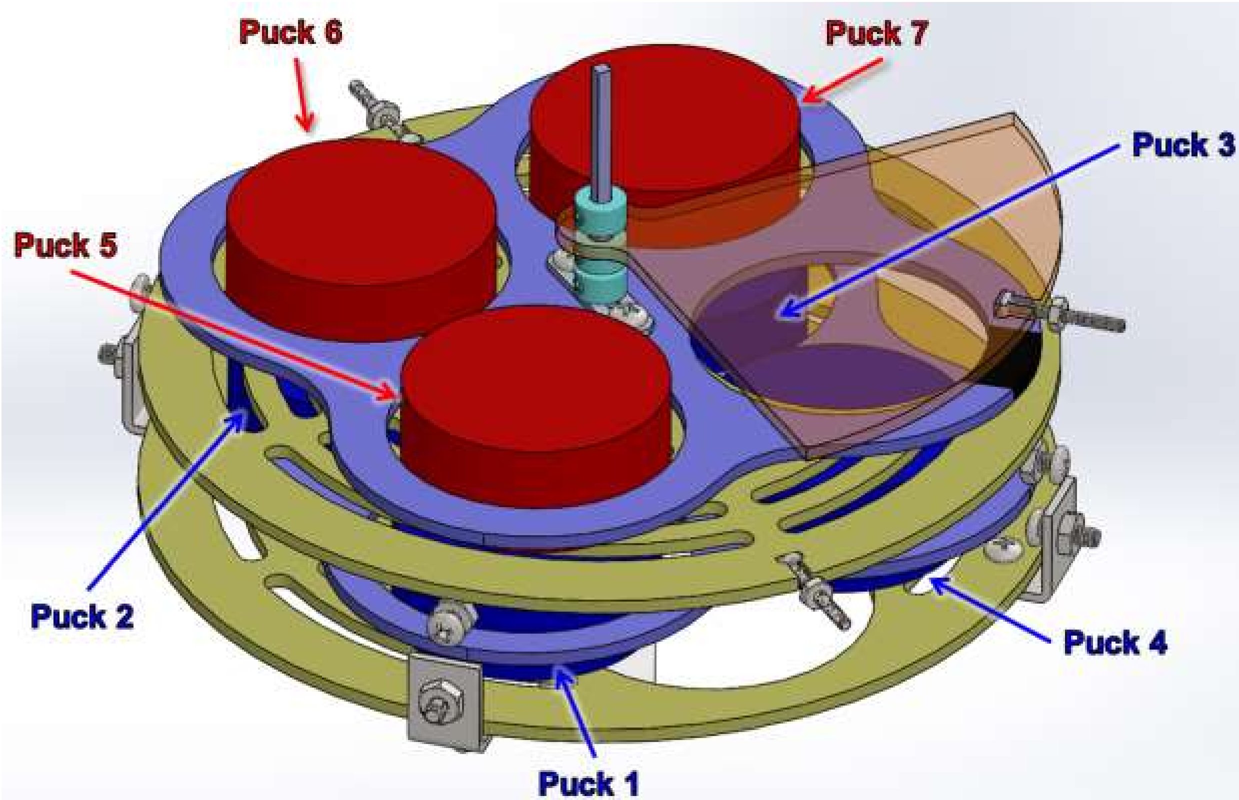

Figure 32. Puck mechanism inner workings.

Figure 32 shows a view of the mechanism internals, with all salt pucks loaded. The mechanism is cycled in a counter-clockwise motion, such that the pucks fall in order from 1 to 7. The first-layer pucks (shown in blue) sit on a plate with a round drop hole that allows them to fall onto the roof. The second-layer pucks (shown in red) sit on a plate with a larger drop hole, rotated 90 degrees to the first layer drop hole, which allows each puck to be dropped into the spots vacated by the first-layer pucks after they drop.

The first puck to fall is Puck 1, when a rotation of 45 degrees brings the puck over the first-layer drop hole and allows it to fall over the target. This creates a vacancy in Puck 1's previous position. An additional rotation of 90 degrees allows Puck 2 to fall, vacates the Puck 2 spot, and allows Puck 5 to fall into the spot previously occupied by Puck 1. The top plate (which is orange and translucent in Figure 32) stops Puck 5 from tilting as it falls. Another 90 degree rotation causes Puck 3 to fall out of the mechanism, vacating its spot, while Puck 6 falls into Puck 2's previous spot. This continues with Puck 7, which falls into Puck 3's spot as Puck 4 drops out of the mechanism.

At this point the first layer is comprised solely of Pucks 5, 6, and 7. There are no more pucks left on the second layer, so the only action accomplished by further 90-degree rotations is the ejection of these pucks from the mechanism.

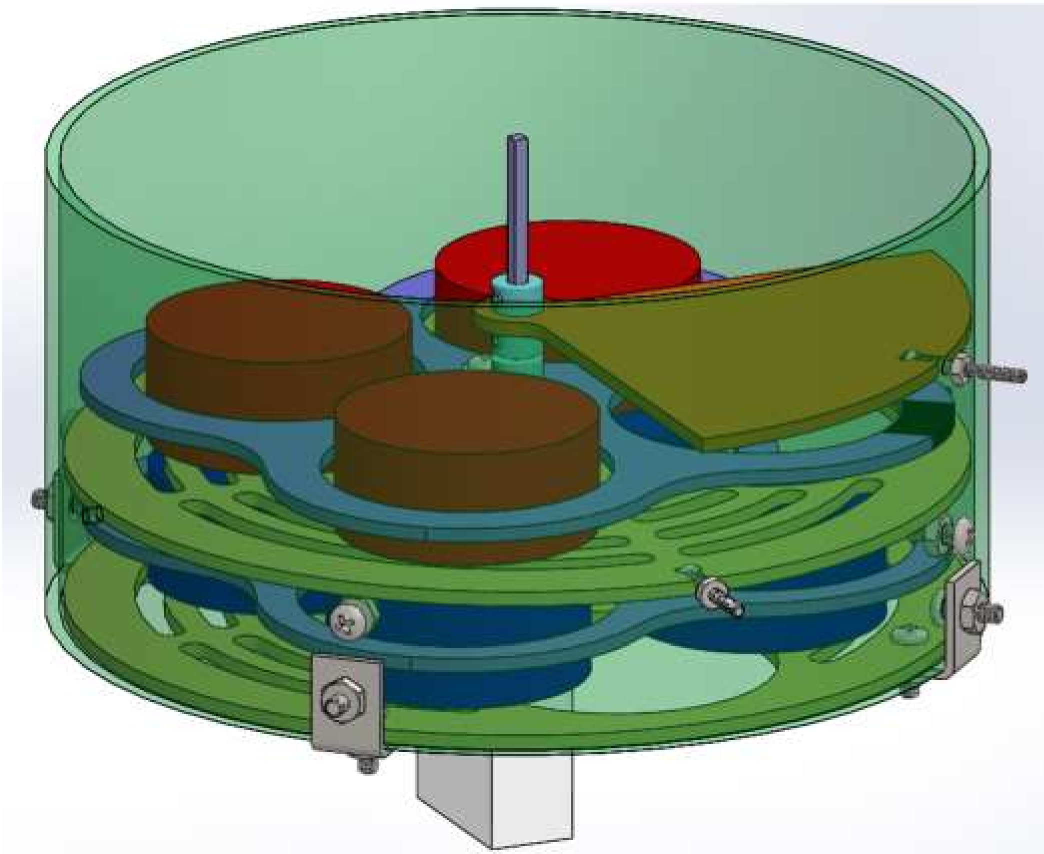

Figure 33. Fully-reloaded puck mechanism.

The mechanism is not entirely straightforward to load (which is an improvement that could be made by future projects), but is simple after conducting several reloads. First, the second-layer spinner is filled with three salt pucks while the fourth spot sits over the second-layer drop hole. Through this fourth position, a salt puck may be dropped directly down into the first layer of the mechanism. Second, the mechanism is cycled while the first layer drop hole is held closed such that pucks do not fall out of the mechanism. In this way, the second-layer pucks fall into, and completely fills, the first-layer spinner. Third, the mechanism is cycled so one of the second-layer spinner holes sits directly below the top plate, and such that two of the first-layer pucks straddle the first-layer drop hole. The spinner is marked with black electrical tape at this position, and this position remains vacant in the next step (see Figure 33). Finally, the second-layer spinner is filled with three salt pucks, neglecting the marked spinner hole.

Inherent in the reloading process is the act of first removing the mechanism from the multirotor (removing the Clevis pins holding it onto the mount tabs) and then removing the mount plate from the mechanism. After reloading, the mount plate is replaced and the mechanism is mounted back onto the multirotor. This mount plate, and the process used to remove and replace it, is shown in Figure 34 in the following section.

7.5.5 Customization of the Mounting Plate

After establishing the final design of the puck mechanism, the next step was to customize the rectangular mounting plate for use with the mechanism. To allow for minimal puck reloading time, the mounting plate would need to be detachable from the mechanism without the use of tools. To accomplish this, a system was developed that would involve raising the mechanism up and into the mounting plate (pictured in white in Figure 34), such that brackets affixed to the mechanisms shell wall would pass through corresponding cutouts in the mounting plate. The mount plate would then be rotated *counterclockwise* with respect to the mechanism, causing the top of the mechanism's brackets to come to rest on the top surface of the mounting plate.

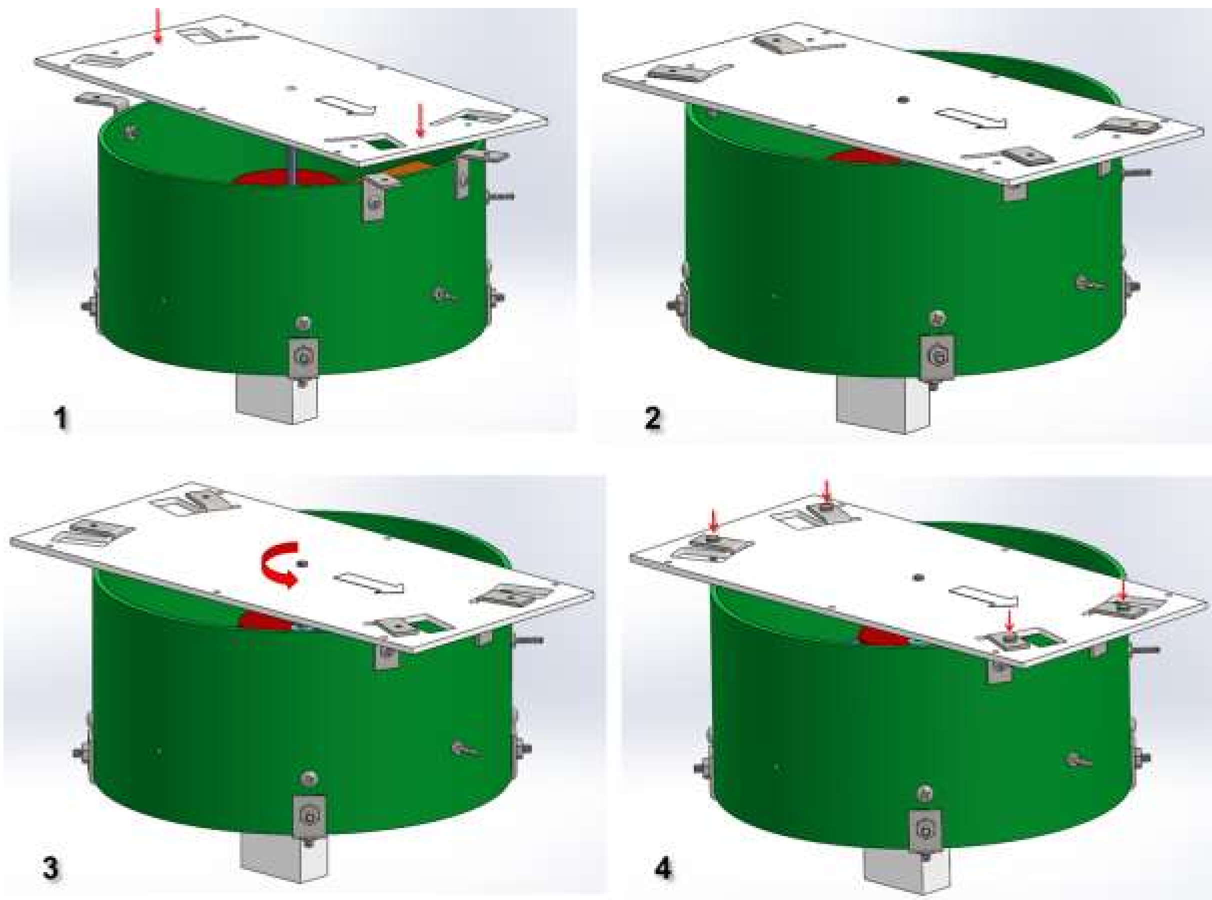

Figure 34. Securing the customized mount plate to the puck mechanism.

Clevis pin clearance holes would be positioned on the mounting plate such that, upon rotating the mechanism into place, clevis pins could be passed through each of the brackets and their respective pin holes in the mounting plate, effectively locking the mechanism into place. Cotter pins would be inserted into each of the clevis pins to prevent them from coming loose. Four areas of contact would be established, using four bracket-clevis pin interfaces.

Figure 34 shows the steps involved in connecting the mechanism to the mounting plate, as would be done after reloading the mechanism; the steps are repeated in reverse to separate the mechanism and mounting plate.

A clearance hole was added into the center of the mounting plate to allow the mechanism's square shaft to pass through, supporting it. These mount plate modifications brought the mass of the puck mechanism mounting plate down to approximately 0.1225kg.

7.5.6 Description of the Motor

The motor used to operate the puck mechanism is a 2-wire VEX 393 motor. This motor has a higher max torque output than a standard VEX motor of similar size. Such a motor was chosen to ensure that it would have enough torque to be connected directly to the shaft, without the need for a gear train. Although a gear train can be used to add a huge amount of torque, it would add complexity to the design, add weight, and reduce the smoothness of the bottom drum surface upon which pucks slide (due to the requirement for more axles and/or screws), creating more potential failure points. The stall torque of this motor is 1.67 N-m, or 14.76 in-lb [58]. This means that the motor could apply a force of 1.67N to a body 1m away. Using the distance between the square shaft and center of the puck holes in the spinners, this means that the motor can apply 31.88N (7.17lb) of force at this radius. Since the force of static friction of a single puck is 0.3233376N (See Appendix C), the total force that the motor needs to resist is 2.26336N for all seven pucks. By subtracting this from the force required to stall the motor at this distance, a surplus of 29.62N is reached. Therefore, the VEX 2-wire 393 motor is completely capable of powering the Puck Mechanism without any form of gear train.

Section 7.7 will expand upon the control of this motor.

7.5.7 Ensuring an Optimal Center of Mass

As discussed in Section 7.1 of the report, it is important to be conscious of the mechanism center of mass at all times, especially when the multirotor is in-flight with the mechanism. Seeing as the multirotor should hover as it drops pucks within small distances of each other, it is acceptable if the center of mass moves slightly along the pitch axis (multirotor left/right) during this part of the operation. This is acceptable because the flight controller of the multirotor is designed to keep the vehicle in a stable hover due to winds or a slightly shifting center of mass. However, the center of mass should remain appreciably along the roll-yaw plane while the loaded multirotor is moving from the ground to the ice dam, and while the empty multirotor is moving from the ice dam to the ground. During these operations, the multirotor is undergoing movement and is more susceptible to destabilizing forces.

SolidWorks was used to determine the center of mass of the mechanism at the following critical times: When the mechanism is fully-loaded, when the mechanism has deployed 1, 2, 3, 4, 5, and 6 pucks, and when the mechanism is empty. The materials and respective densities used in this simulation ensure that the simulation provides an accurate representation of the center of mass states of the real-life prototype. For high stability, it is reasonable that the center of mass should not shift more than 0.5in along the pitch axis (multirotor left/right, along the Z-axis in Figure 35) from the center of the multirotor.

Figure 35 defines the central location, or origin, of the puck mechanism from which the center of mass coordinates are measured from. The mechanism's origin is located at the intersection of the front, right, and top planes (the top plane being flush with the bottom of the shell wall and bottom plate). The location of the center of mass is indicated by the black and white circle.

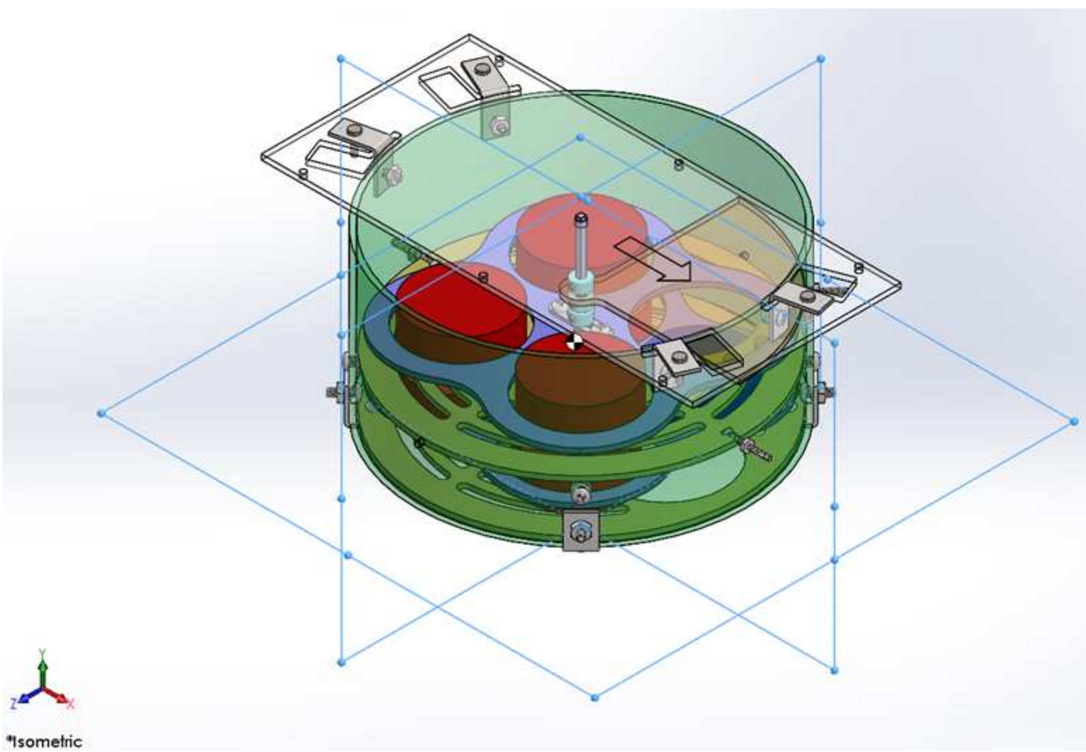

Figure 35. Puck mechanism center of mass and origin.

Figure 36 shows the mechanism's center of mass in its initial state, fully loaded with seven pucks. This figure is included to provide a visual perspective for the center of mass coordinates of the initial state. In each view, the center of mass is indicated by a red arrow.

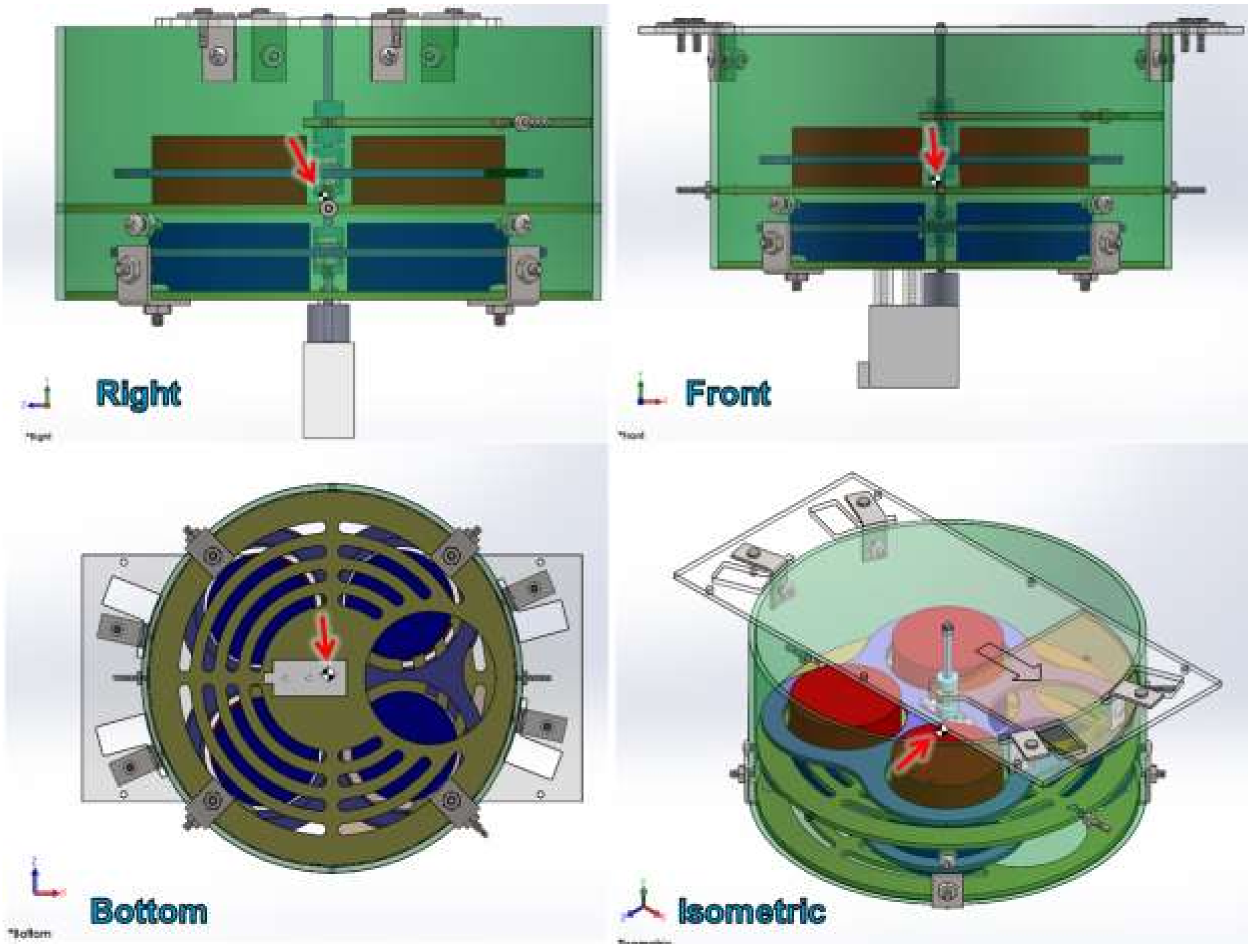

Figure 36. Puck mechanism center of mass, as seen from the right, front, bottom, and isometric perspectives.

A total of eight center of mass coordinates were determined to examine how the X, Y, and Z (roll, yaw, and pitch axes, respectively) coordinates change as the mechanism deploys its load of pucks. These center of mass coordinates can be seen in Table 4, with measurements taken in the fully-loaded state, immediately after each of the seven pucks fall from the mechanism, and in the empty state.

Table 4. Puck mechanism center of mass with respect to time.

	Roll (x) [in]	Yaw (y) [in]	Pitch (z) [in]	Comments
State 1 (Fully Loaded)	-0.0843	1.51879	0.07569	
State 2 (Puck 1 Released)	-0.12785	1.58181	0.12343	
Change from 1-2	-0.0436	0.0630	0.0477	
State 2 (Puck 1 Released)	-0.12785	1.58181	0.12343	
State 3 (Puck 2 Released)	0.01871	1.55756	0.12745	
Change from 2-3	0.1466	-0.0242	0.0040	
Change from 1-3	0.1030	0.0388	0.0518	
State 3 (Puck 2 Released)	0.01871	1.55756	0.12745	
State 4 (Puck 3 Released)	0.01452	1.52933	-0.03126	
Change from 3-4	-0.0042	-0.0282	-0.1587	
Change from 1-4	0.0988	0.0105	-0.1070	
State 4 (Puck 3 Released)	0.01452	1.52933	-0.03126	
State 5 (Puck 4 Released)	-0.16846	1.49605	-0.02793	
Change from 4-5	-0.1830	-0.0333	0.0033	
Change from 1-5	-0.0842	-0.0227	-0.1036	
State 5 (Puck 4 Released)	-0.16846	1.49605	-0.02793	
State 6 (Puck 5 Released)	-0.18492	1.58159	0.17226	
Change from 5-6	-0.0165	0.0855	0.2002	
Change from 1-6	-0.1006	0.0628	0.0966	
State 6 (Puck 5 Released)	-0.18492	1.58159	0.17226	
State 7 (Puck 6 Released)	0.01917	1.68576	0.19093	
Change from 6-7	0.2041	0.1042	0.0187	
Change from 1-7	0.1035	0.1670	0.1152	Largest change in position from State 1
State 7 (Puck 6 Released)	0.01917	1.68576	0.19093	
State 8 (Empty)	0.02178	1.81539	-0.03774	
Change from 7-8	0.0026	0.1296	-0.2287	Largest change in position from a previous State
Change from 1-8	0.1061	0.2966	-0.1134	

The mechanism's center of mass never shifts more than 0.2287in from a previous state, and never shifts more than 0.1152in from the initial state (State 1). Additionally, knowing that the center of mass has a z-coordinate of 0.07569in in its initial state (along the pitch axis), the center of mass is determined to never be more than 0.19089in from the center of the mechanism, along the pitch axis. This is acceptably close to its center along the pitch axis for the duration of the operation, given the previous judgement that the center of mass should not shift more than 0.5in along the pitch axis.

The amount that the center of mass shifts along the yaw axis is insignificant (since the presence of the puck deployment mechanism lowers the vehicle's center of mass, which is desirable for stability. The shift along the roll axis (multirotor forward/backward) is largely insignificant due to the presence of mounting brackets that slide along that direction, allowing for the mechanism to be placed in the proper position with respect to the multirotor's center of mass. Table 4 shows that the center of mass does not shift more than 0.5in along this axis anyways.

7.5.8 Overall Mass and Height Check of the Final Design

Table 5 outlines the mass of each individual component as determined in SolidWorks, along with the total mass with and without a full load of pucks.

Table 5. Puck mechanism mass breakdown.

CD CHANGER MECHANISM (WITOUT MOUNT COMPONENTS)	TOTAL MASS (kg)
VEX High Torque Motor	0.0914
Bottom Plate	0.0728
Middle Plate	0.07
Top Plate	0.0292
Bottom Spinner	0.0277
Middle Spinner	0.0378
Mounting Plate	0.1225
Body Tube	0.24243
Square Shaft	0.00921
4-40 x 1" Screws x3	0.00354
8-32 x 0.5" Screws x8	0.01464
Type 1 7/8"x7/8" Brackets x4	0.03784
Shaft Couplers x6	0.03084
6-32 x 5/8" Screws x6	0.00594
6-32 Nut x4	0.00416
8-32 Nut x8	0.0108
4-40 Nut x5	0.00275
TOTAL	**0.81355**
Salt Pucks x7	0.7
Loaded Total	**1.51355**

The total loaded mass is 1.51355kg. This is well below the 2.5kg payload capacity of the DJI S900 multirotor, and allows an additional 0.98645kg for the to-be-designed means for mounting the electronics to the mechanism, and the mount tabs. The mass of the actual prototype, with electronics attached (discussed later) is 0.868kg empty, and 1.568kg filled. This is well within the payload capacity of the multirotor, and future projects may wish to incorporate many more pucks.

Additionally, the mechanism has an overall height of 6.75in which is smaller than the previously established 11in height constraint.

Figures 37 and 38 show the completed first generation prototype of the puck deployment mechanism, both empty and with a full load of Roofmelt ice pucks.

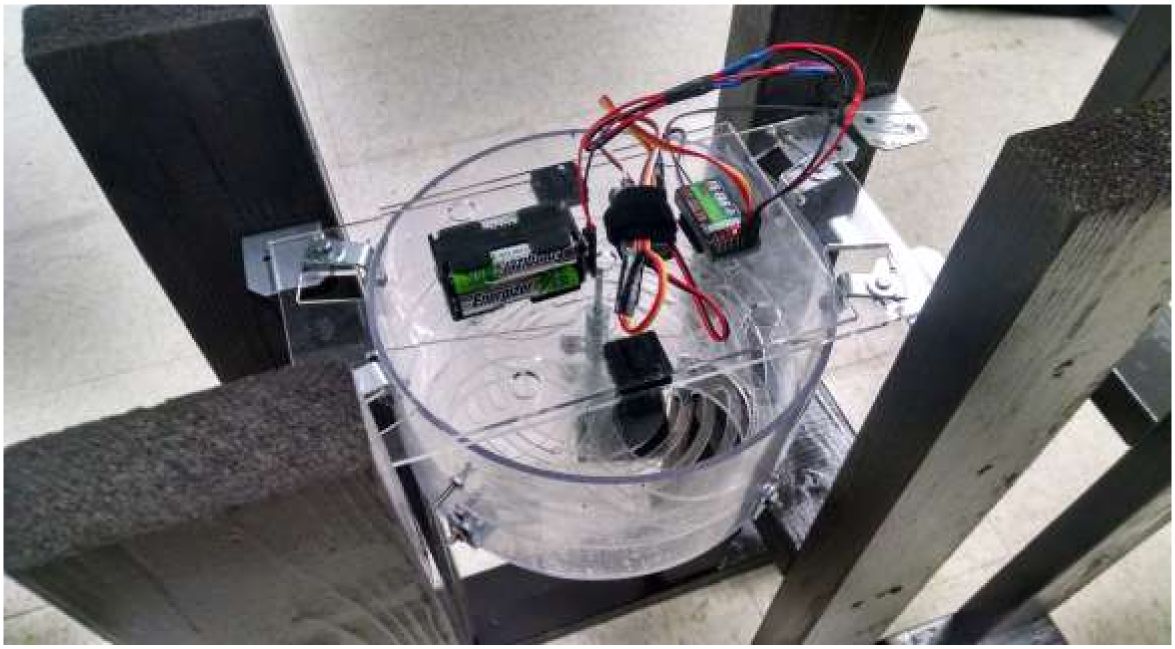

Figure 37. Empty puck mechanism prototype, with electronics plate attached, on test stand.

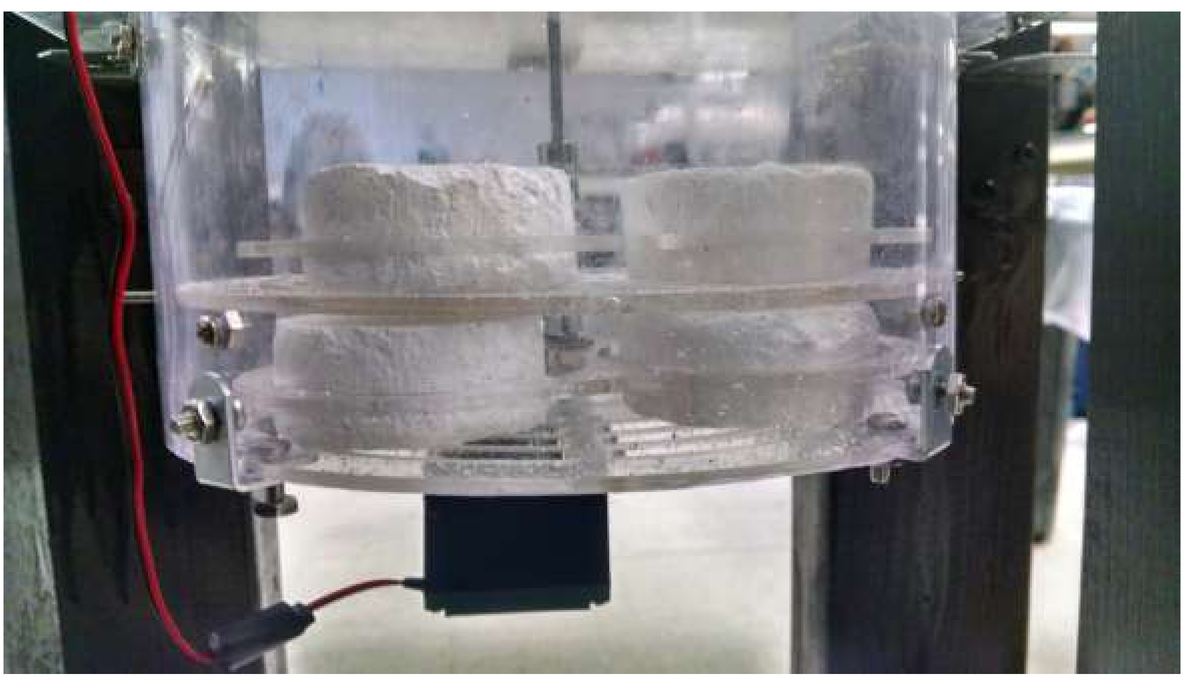

Figure 38. Fully-reloaded puck mechanism prototype on test stand.

7.6 Final Design of the Granular Mechanism

7.6.1 General Description of Purpose

The functionality of the Granular Mechanism is to transport and then distribute granular salt both behind and over the top of ice dams. This mechanism will help to both control and remove ice dams. After the puck deployment mechanism has deployed deicing pucks such that channels are created in the ice dam, the granular salt deployment mechanism will distribute salt in the area behind the dam, providing a means for a brine solution to be maintained in this area. This brine solution will flow through the existing channels, preventing them from re-filling with ice after the deicing pucks and their residue have been entirely spent. This mechanism may also aid in the gradual melting of the entire ice dam by spreading granular salt over its exposed surface area.

Other surfaces may also be de-iced in winter time, such as sidewalks, driveways, etc. Granular salt is the most commonly used and available material to perform such tasks, so this mechanism could be applied here as well.

7.6.2 Determining a Mass Limit for the Mechanism

As with the puck deployment mechanism, a minimum salt load of 0.7kg (and a mechanism empty mass of 1.8kg) is desired. Scotwood Road Runner Pet-Safe Ice Melt [47] is the salt used here. Testing yielded that 48oz (0.001420 m^3) of this ice melt has a mass of 1.239kg. It is a simple matter to calculate the density at 872.54 kg/m^3 (24.71 kg/ft^3). A salt mass equivalent to the puck mechanism capacity (0.7kg) would have a volume of 8.023E-4 m^3, or 3.39 cups.

7.6.3 Design Development/Construction

A vinyl gutter funnel, shown in Figure 39, forms the body of this design. The flat faces provided by this object were highly desirable from a manufacturability standpoint. This funnel has a large opening on the bottom; in order to control the mass flow rate of salt from this aperture, a diameter-reducing component is required.

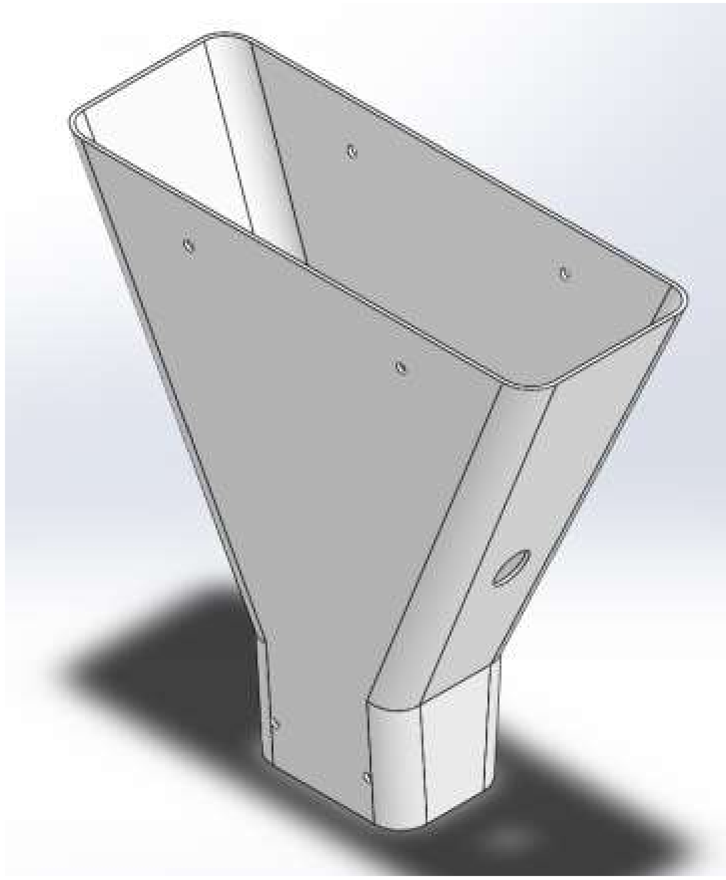

Figure 39. Granular mechanism "gutter funnel" body.

The funnel is 9 inches high and 9 inches wide at maximum width. The bottom opening is roughly 2.75 inches wide and 1.9 inches deep on the inside (the plastic is flexible, so there are relatively wide tolerances here). The internal volume of the funnel is about 1847.139 cm^3 (7.81 cups). 0.7kg of salt corresponds to 3.39 cups of salt, so 7.81 cups corresponds to 1.613kg of salt. Without electronics, the granular mechanism must have a mass of less than 887g to remain under the 2.5kg payload constraint with this mass of salt loaded.

The bottom portion of the funnel is about 2 inches high. It was determined that a lightweight PLA 3D-printed insert of these dimensions would be the best course of action for reducing the diameter, allowing the salt to flow through a much smaller, constant-diameter "neck." A hole 1 inch in diameter is sufficient to provide a good mass flow without all of the salt spontaneously rushing out. As salt falls through the reducer, the diameter decreases from the initial square opening to a hole 1 inch in diameter and 0.25 inch in height. The piece includes screw holes on the sides and bottom, used to secure it in place with respect to the funnel and to help secure the motors to the mechanism body, respectively. See Figure 40 for a visual representation of this part.

Figure 40. Funnel outlet diameter reducer.

48oz of granular ice melt (1.239kg) takes approximately 18.37s to fall through this device. This results in a mass flow rate of 67.45 g/s, or 0.06745 kg/s. The time to empty the mechanism is sufficient to make multiple controlled drops by opening and closing a release door below the hole. A servo may be used to rotate such a door into or out of the path of the falling salt. In its open position, the door would be rotated a minimum number of degrees away from the closed position, such that the flow of salt could be rapidly stopped if need be.

This door only works if the salt can flow; under certain conditions (e.g. humidity or irregularities in the sizes of the salt grains) it was hypothesized that the salt may need to be stirred in-flight. The concept of an agitator, used to disturb the salt should a clog occur, was developed by using a motor to rotate an auger or plate. A decision was ultimately made to incorporate an agitator that is mounted horizontally inside the funnel, as opposed to being parallel with the motion of the falling salt. Mounting a motor to turn a vertical agitator introduced manufacturability concerns in regards to motor mounting and positioning. Mounting it on top of the mechanism risks hitting the undercarriage-mounted battery of the multirotor and disallows convenient electronics plate placement, and mounting it on bottom is not an option lest the salt be unable to fall out of the mechanism. Mounting the agitator in the former configuration (horizontally) allows incorporation of the motor along the side of the funnel close to the diameter reducer, such that salt falls down onto it.

The motors would be mounted such that the mechanism is symmetrical about the roll/yaw plane, promoting center of mass placement on this plane. A custom-designed metal frame using 3003 formable aluminum could be used to secure the motors next to the sloped surface of the funnel. The frame would be bent to shape, allowing the bottom of the frame to be screwed into the bottom of the 3D-printed flow limiter, and the top of the frame to be screwed into the bottom of the rectangular mounting plate. Ultimately, this frame would resemble a "handle" coming off one side of the funnel. The swivel door servo would mount directly into the bottom section of the frame, and the agitator motor would be mounted to the middle portion of the frame using additional pieces of formable aluminum.

An exploded view of the final granular mechanism assembly can be seen below in Figure 41. Each of the critical parts is numbered in the exploded view. The corresponding name for each numbered part is as follows:

1. Mounting Plate
2. Gutter Funnel
3. Funnel Outlet Reducer
4. Swivel Release Door
5. Swivel Release Door Hub
6. Swivel Release Door Shaft
7. VEX 269 Motor
8. Agitator
9. Agitator Shaft
10. VEX Servo
11. Nylon Sleeve
12. Double Sealed Bearing
13. Frame Piece 1
14. Frame Piece 2
15. Frame Piece 3
16. Frame Piece 4

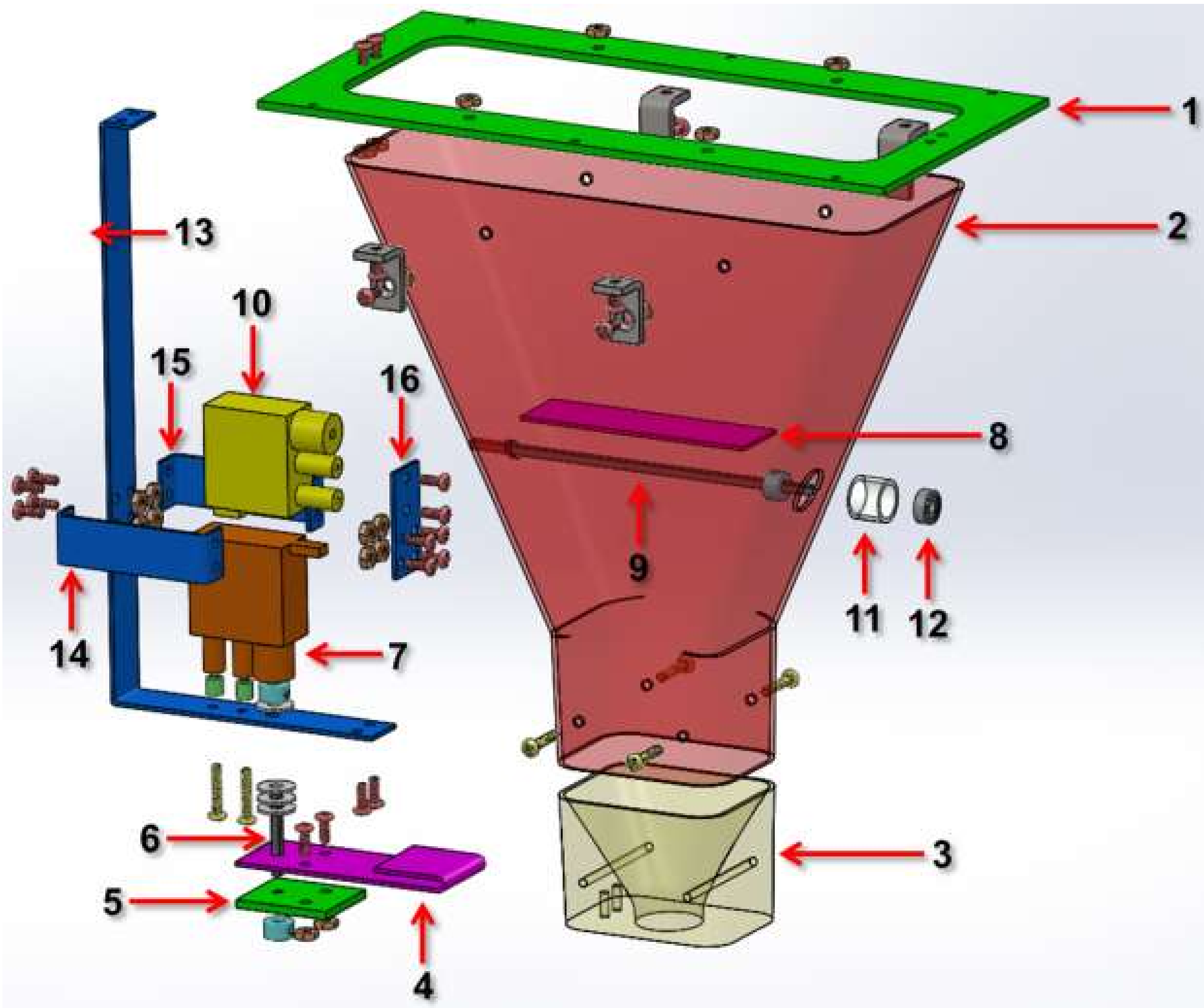

Figure 41. Granular mechanism exploded view.

Operation of the granular mechanism is controlled by the VEX 269 motor (agitator, 10) and VEX servo (door, 7). The VEX servo (7) rotates the swivel release door (4) via the swivel release door hub (5) and swivel release door shaft (6) between its opened and closed positions. In its closed position, the swivel release door blocks salt from flowing out of the bottom of the funnel outlet reducer (3); when the swivel release door is in its open position, salt is free to flow out of the bottom of the funnel outlet reducer. The VEX 269 motor (10) rotates the agitator (8) via the agitator shaft (9). When continuously rotated, the agitator (8) stirs the salt contained within the funnel (2), helping to avoid clumping of the salt, and ensuring a continuous flow out of the bottom of the funnel outlet reducer.

To begin the assembly process of the granular mechanism, the top (wide section) of the funnel (2) is inserted through the large opening in the mounting plate (1), such that the top of the funnel is flush with the top surface of the mounting plate. Then, four 1” x 5/8” screw brackets are used to secure the funnel and mount plate to each other with 8-32 x 3/8in screws and hex nuts. Next, the funnel outlet reducer (3) is inserted through the top of the funnel and pressed down through the funnel's square-shaped tapering outlet, such that the bottom of the reducer is flush with the bottom surface of the funnel. It is critical that the two screw holes on the bottom of the funnel outlet reducer are positioned on the motor-side of the funnel as seen in the left side of Figure 41, to allow fastener connection. Four 6-32 x 3/4in screws are then used to attach the funnel and funnel outlet reducer, keeping the reducer securely in position.

Next, the VEX Servo (10) is attached to frame piece 1 (13) with two 6-32 x 3/4in screws. Two 1/4in #6-clearance spacers are needed between frame piece 1 (13) and the screw mounts in the VEX Servo to ensure that the servo's rotating piece does not come in direct contact with the frame. Frame pieces 2 and 3 (14 and 15) are attached to frame piece 1 (13) via 6-32 x 3/8in screws and nuts. Frame piece 4 (16) is then attached to frame pieces 2 and 3 (14 and 15) via 6-32 x 3/8in screws and nuts. Together, these four frame pieces comprise the "motor frame". Next, the VEX 269 motor (7) is mounted to frame piece 4 (16) using two 6-32 x 3/8in screws. After the VEX Servo and VEX 269 motor have been mounted to the motor frame, the frame piece 1 - and everything attached to it - is mounted to the left side of the mounting plate (1) and to the bottom of the funnel outlet reducer (3).

Next, the double sealed bearing (12) is hand press-fit into the nylon sleeve (11), and the nylon sleeve is glued into its respective hole-cutout in the funnel (2) using JB Weld. Then, holding a 3/16in-ID shaft collar inside of the funnel behind the nylon sleeve, the agitator shaft (9) is passed through the double sealed bearing (12), collar, and its clearance hole on the other side of the funnel, finally entering into the clutch of the VEX 269 motor (7). The collar is tightened to the agitator shaft (9) via a set screw to ensure that the agitator shaft does not come loose. Next, the agitator (8) is glued to the shaft using JB Weld, centered lengthwise along the exposed area of the shaft.

The swivel release door hub (5) is connected to the swivel release door (4) using 6-32 x 3/8in screws and nuts. Then, the swivel release door shaft (6) is passed through the swivel release door hub and swivel release door. Three #10 PTFE washers are placed on the swivel release door shaft, coming to rest on the surface of the swivel release door. This comprises the "swivel release door assembly." Next, a #10 PTFE washer, followed by a 3/16in-ID shaft collar, is placed on frame piece 1 (13) directly below the clutch of the VEX servo (10). The swivel release door assembly is then installed by passing the swivel release door shaft through frame piece 1, the #10 PTFE washer, and the 3/16in-ID shaft collar before finally entering the servo clutch. The collar closest to the VEX servo's clutch is tightened to the swivel release door shaft with a set screw. Another 3/16in-ID shaft collar is then inserted onto the swivel release door shaft directly below the swivel release door hub and tightened to the swivel release door shaft. Together, these collars keep the swivel release door shaft and the remainder of the swivel release door assembly from moving up or down. This concludes the assembly process for the granular mechanism.

During the construction and assembly processes of the actual prototype, clamps are used instead of JB Weld to secure the agitator to its shaft. Additionally, the nylon sleeve (11) and double sealed bearing (12) were excluded from the prototype due to the low friction present without them. These are structural and weight-saving measures, respectively.

7.6.4 How the Granular Mechanism Works

Reloading the granular mechanism is relatively simple compared to that of the puck mechanism. The operator must remove the mechanism from the multirotor and remove the electronics mounting plate, which sits over the wide, open end of the funnel. After ensuring that the swivel release door is closed and the agitator is not spinning, the operator pours granular salt into the funnel until the salt level reaches the tops of the hex nuts securing the funnel's mounting plate brackets. See Figure 42 for a visual representation of this fill line. Filling the salt up to this level corresponds to approximately 48oz of salt. Once the mechanism has been loaded, the electronics mounting plate is reinstalled onto the mechanism.

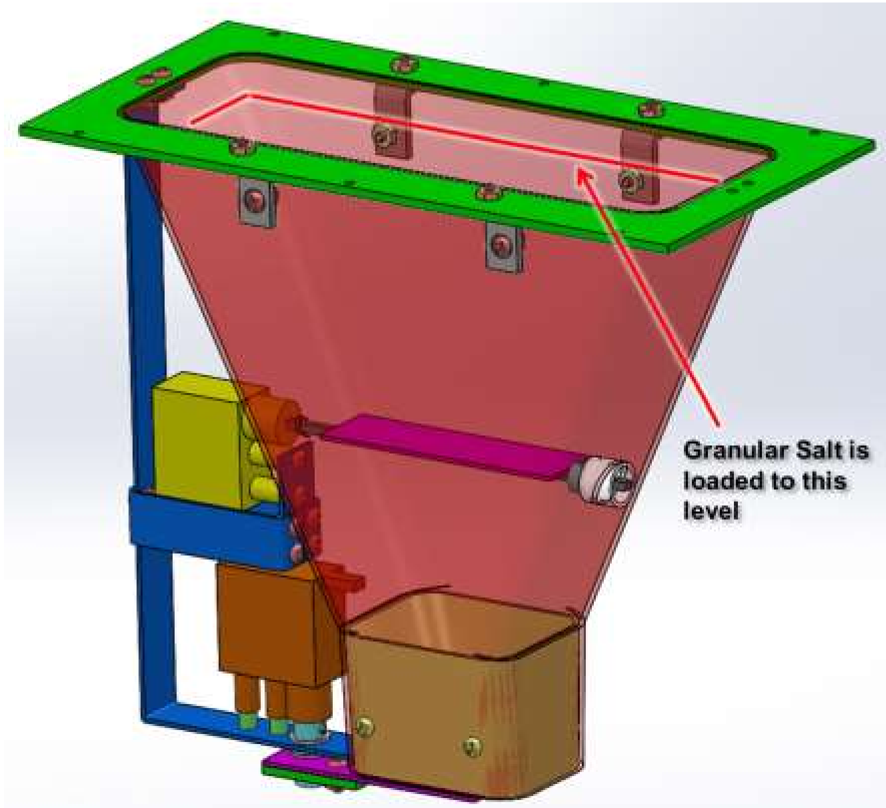

Figure 42. Empty granular mechanism.

To drop salt, the operator operates the transmitter such that the swivel release door rotates approximately 45 degrees from its closed position, allowing salt to begin flowing from the mechanism and into the bucket below. See Figure 43, showing the swivel release door in its closed and open positions.

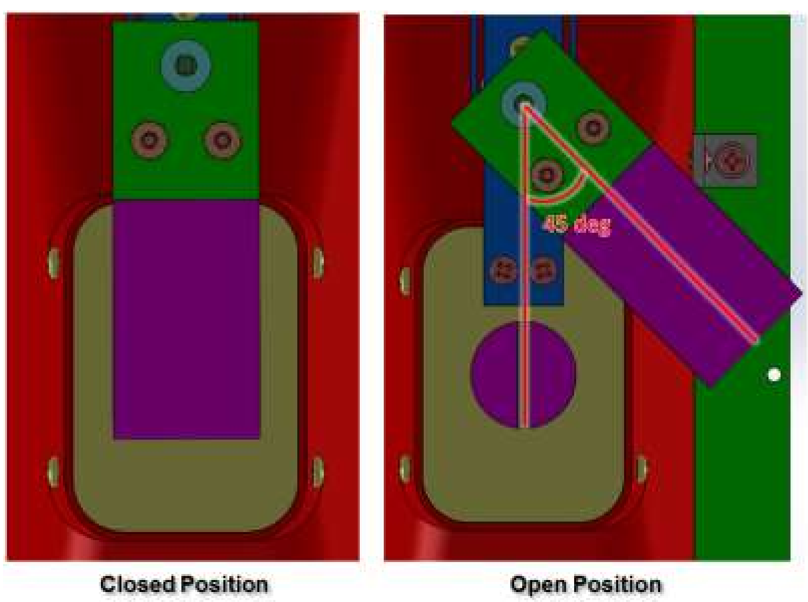

Figure 43. Granular mechanism swivel door.

To ensure consistent salt flow, the operator may use the transmitter to begin rotating the agitator immediately after (but not before) the swivel release door has been opened, to promote uninhibited salt flow. The agitator is particularly useful in situations where the inside surfaces of the funnel, or the exposed surface of the salt, have become damp due to weather conditions. Figure 44 shows the relative motions of the agitator and swivel release door.

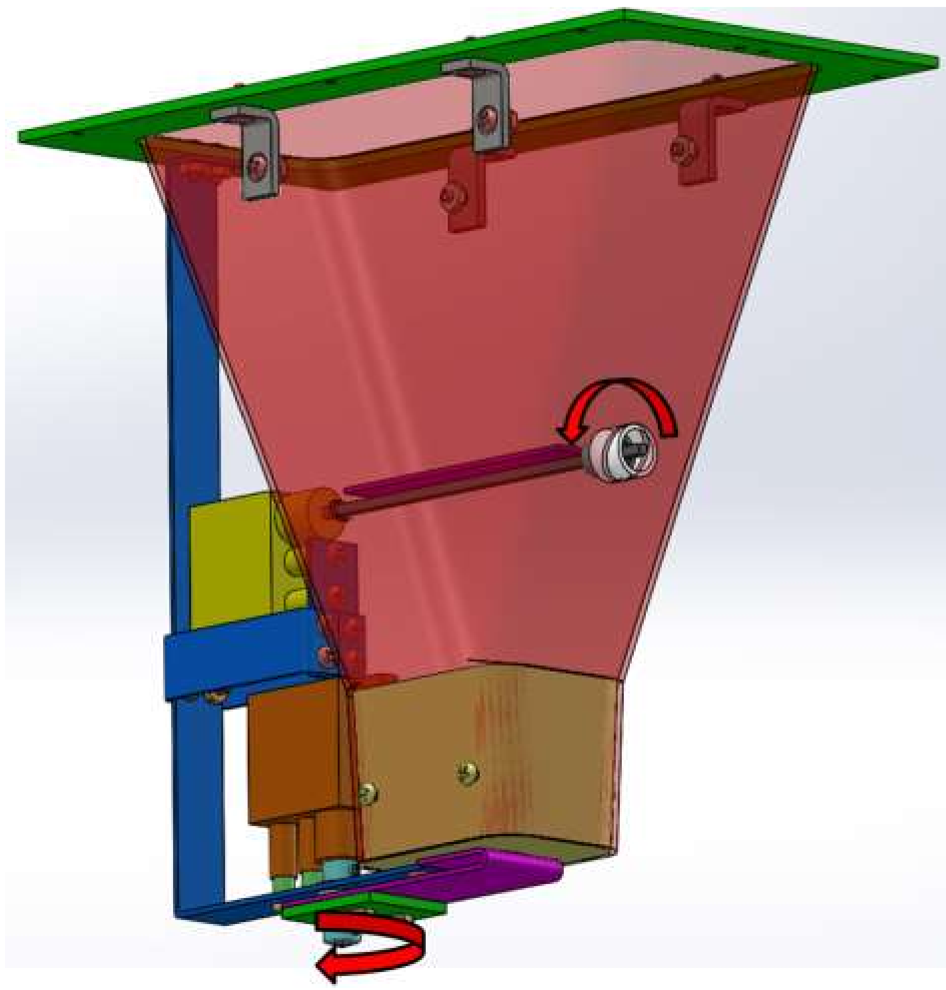

Figure 44. Granular mechanism agitator and swivel release door rotation.

Once the entire load of salt has been released from the mechanism, the operator uses the transmitter to stop the agitator from rotating and to return the swivel release door to its closed position. At this point, the mechanism is ready to be reloaded for another run.

7.6.5 Customization of the Mounting Plate

The customization of the mounting plate for the granular mechanism was largely established in Section 7.6.3. As discussed, the mounting plate has a large cutout in its center to fit the top portion of the funnel. This large cutout also serves as means for filling the funnel with granular salt. Unlike the puck mechanism, the granular mechanism does not need to be disassembled from the mounting plate to be refilled; rather, it is necessary only for the mechanism to be detached from the multirotor, and the electronics plate to be temporarily moved. The mounting plate can be considered permanently attached to the mechanism, seeing as it serves as a common connection point for the frame and funnel.

Additional screw clearance holes would be added to the mounting plate to allow for mounting of the aluminum frame via screws, as well as for the installation of brackets to more rigidly connect the funnel and mounting plate. Ultimately, these modifications brought the mass of the granular mechanism mounting plate down to 0.05877kg.

7.6.6 Finite Element Analysis of the Rectangular Mounting Plate

The granular mechanism's rectangular mounting plate has more material cut away than the puck mechanism's plate, compared to the generic plate template used by both mechanisms. Therefore, a Finite Element Analysis was performed on the granular mechanism's mounting plate to ensure that the 0.125in material thickness of the acrylic mounting plate would be sufficient for supporting the maximum possible 2.5kg mechanism mass. This mass was distributed over a 2in long region in the middle of each side of the mounting plate, under the assumption that this would create large stresses within the part.

In the SolidWorks simulation, the mounting plate was fixtured in its four corners where it comes in contact with each of the mounting units, as well as at the locations where it is supported by the four funnel-mounting plate brackets (where little bending occurs). An equivalent force of 24.525N was applied over the previously described regions of the mounting plate, distributing one half of the force (12.2625N) to each side in the corresponding area. In Figures 45 and 46, the top view shows the fixtured areas, and the bottom view shows the areas where the forces were applied.

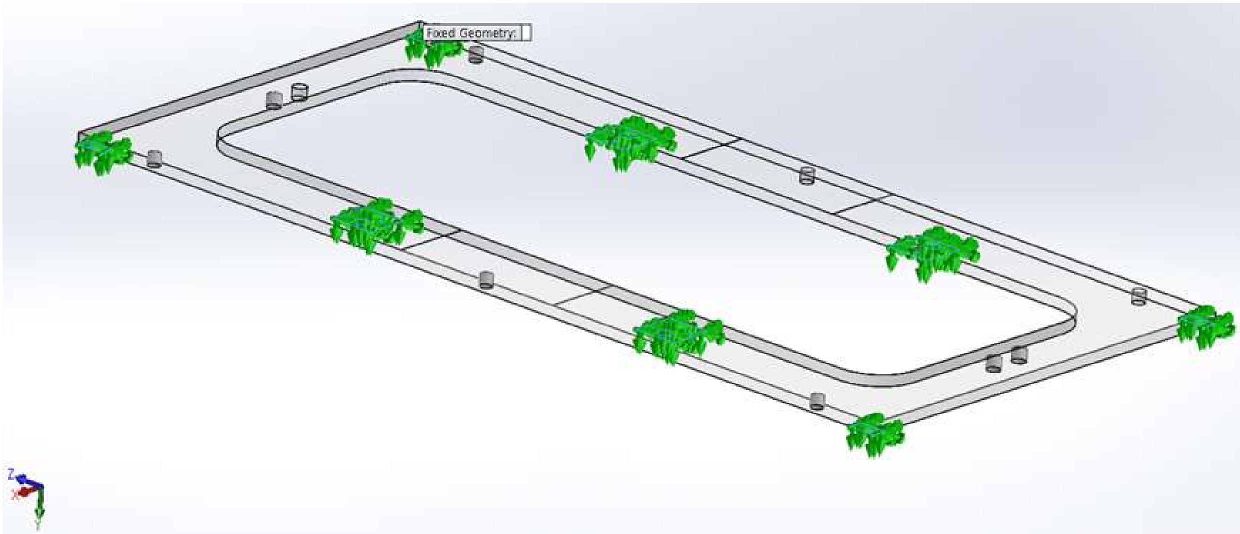

Figure 45. Granular mechanism Finite Element Analysis fixtures.

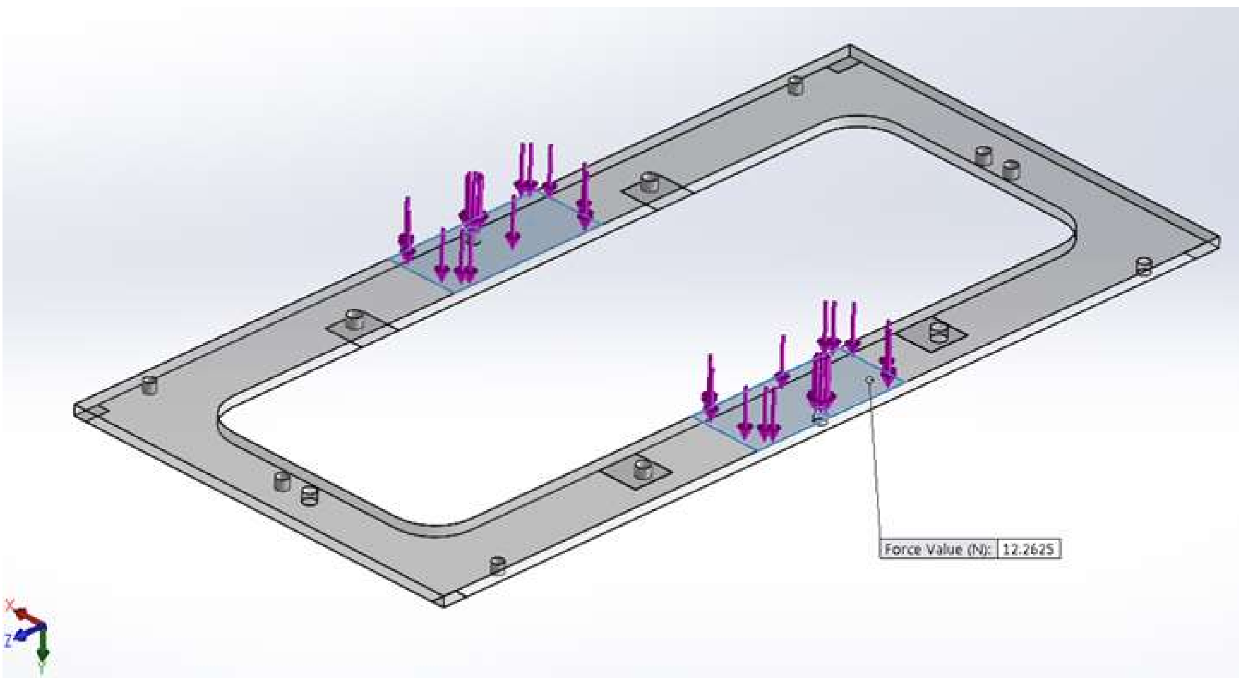

Figure 46. Granular mechanism Finite Element Analysis forces.

After running the finite element analysis, results yielded that, under the previously specified conditions, the mounting plate deforms a maximum of 0.2209mm (0.0087in), and experiences a maximum von Mises stress of 3.962MPa. Seeing as the material has a yield strength of 45.00MPa, the mounting plate is more than capable of handling the previously stated maximum von Mises stress. The deformation is negligible. Figures 47 and 48 show the results of the deformation and von Mises stress analyses, respectively.

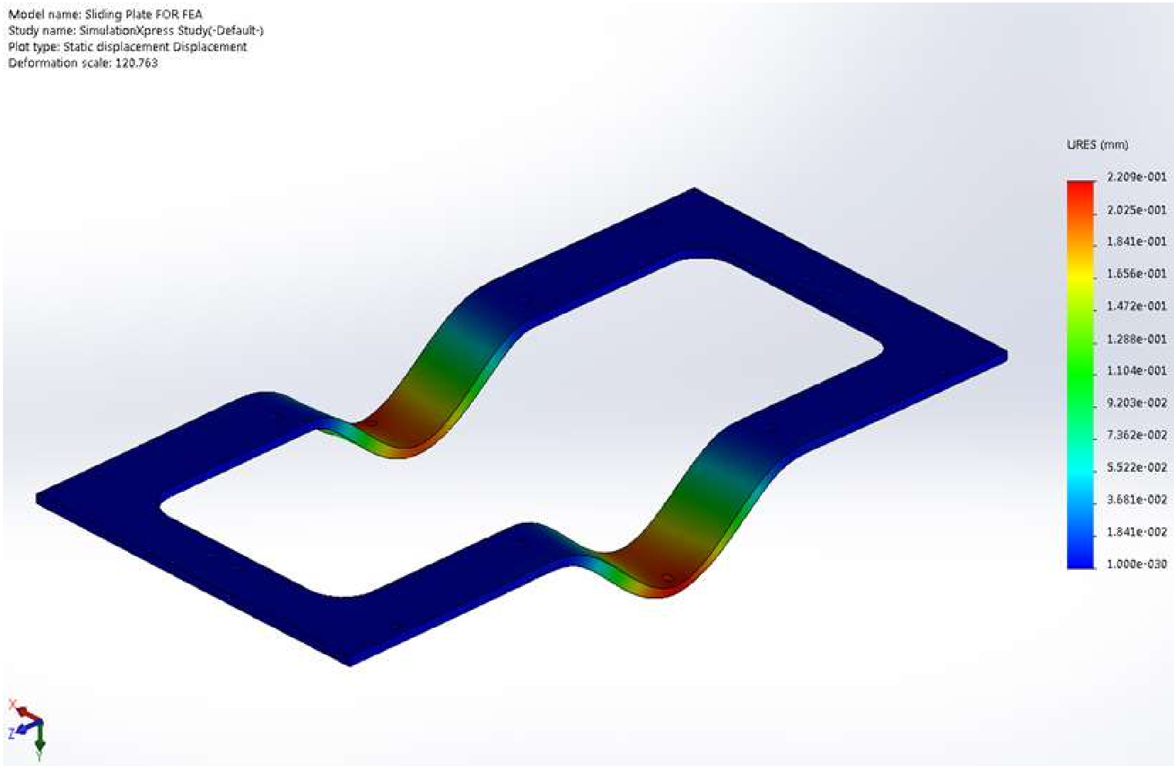

Figure 47. Granular mechanism deformation analysis.

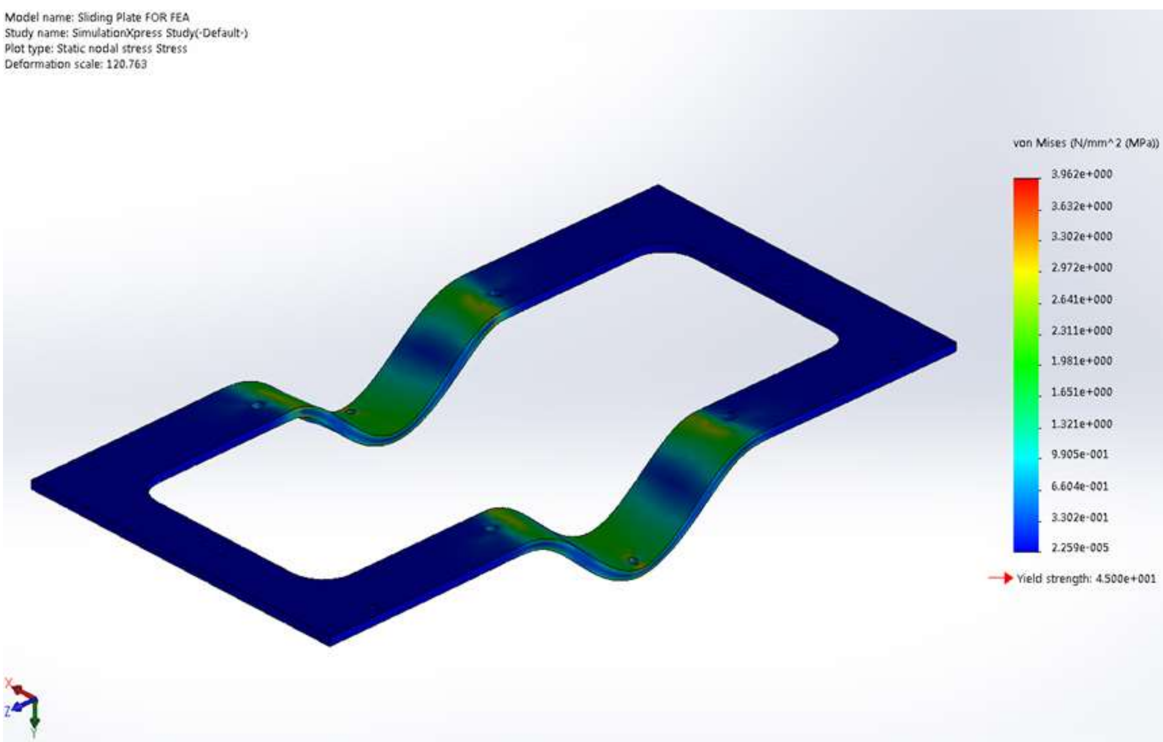

Figure 48. Granular mechanism von Mises stress analysis.

7.6.7 Description of the Motor and Servo

The agitator uses a VEX 2-wire 269 motor. The stall torque is 0.97N-m [59]. This means that the motor can apply a force of 0.97N to a body 1m away. Since the agitator is roughly 2cm in width, the motor would have to apply torques on either side of the center of rotation. Assuming a simplified system of two point forces, each 1cm away from the shaft, each side can support a maximum force of 48.5N. The actual system is comprised of a distributed load over the agitator's surface area, so the real force limits may be lower. Regardless, the agitator should only be used to loosen salt in the event of a clog, due to the high forces it may be exposed to.

The trapdoor on the bottom of the mechanism bears no forces in the direction of rotation; it only bears the weight of gravity due to the salt in the mechanism. Therefore, potential torque on the swivel release door motor is negligible; the ability to accurately control the door's position is most important. The presence of distinct closed/open states is necessary, such that salt does not leak out in the closed state, nor is it's flow hindered by the door in the open state. An ideal actuator for this task is the VEX 3-wire Servo [58]. This servo has a range of motion of approximately 100 degrees, which is plenty to open and close a 1in-diameter hole from a point of rotation that is approximately 2.5in away.

Section 7.7 will expand upon the control of the motor and servo.

7.6.8 Ensuring an Optimal Center of Mass

Just as a center of mass analysis was completed for the puck mechanism, the same analysis must also be completed for the granular mechanism. As previously discussed, it is acceptable for the center of mass to move along the multirotors roll/yaw plane (forward/backward), and to move only very slightly (within 0.5in of the mechanisms center) along the pitch axis (multirotor left/right).

SolidWorks was used to determine the center of mass of the granular mechanism at the following critical times: When the mechanism is fully-loaded with the swivel release door closed, when the mechanism is fully-loaded with the door open, when the mechanism is empty with the door open, and when the mechanism is empty with the door closed. Rotation of the agitator has a negligible effect on the position of the center of mass. A volume of granular salt was modeled in SolidWorks for the analysis, and was assigned the density of the magnesium chloride used in testing. The volume of salt within the granular deployment mechanism is shown in Figure 49.

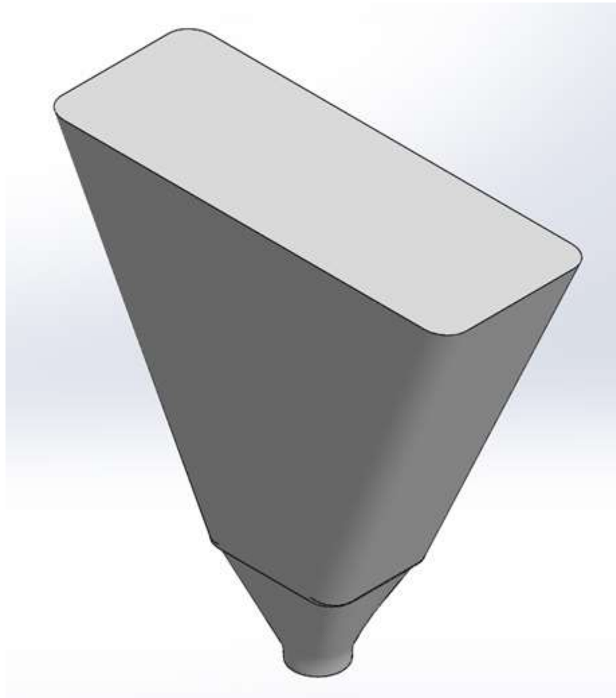

Figure 49. Granular mechanism salt volume.

Figure 50 defines the central location, or origin, of the granular mechanism from which the center of mass coordinates are measured from. The mechanism’s origin is located at the intersection of the front, right, and top planes (the top plane being flush with the bottom of the funnel and funnel outlet reducer). The location of the center of mass is indicated by the black and white circle.

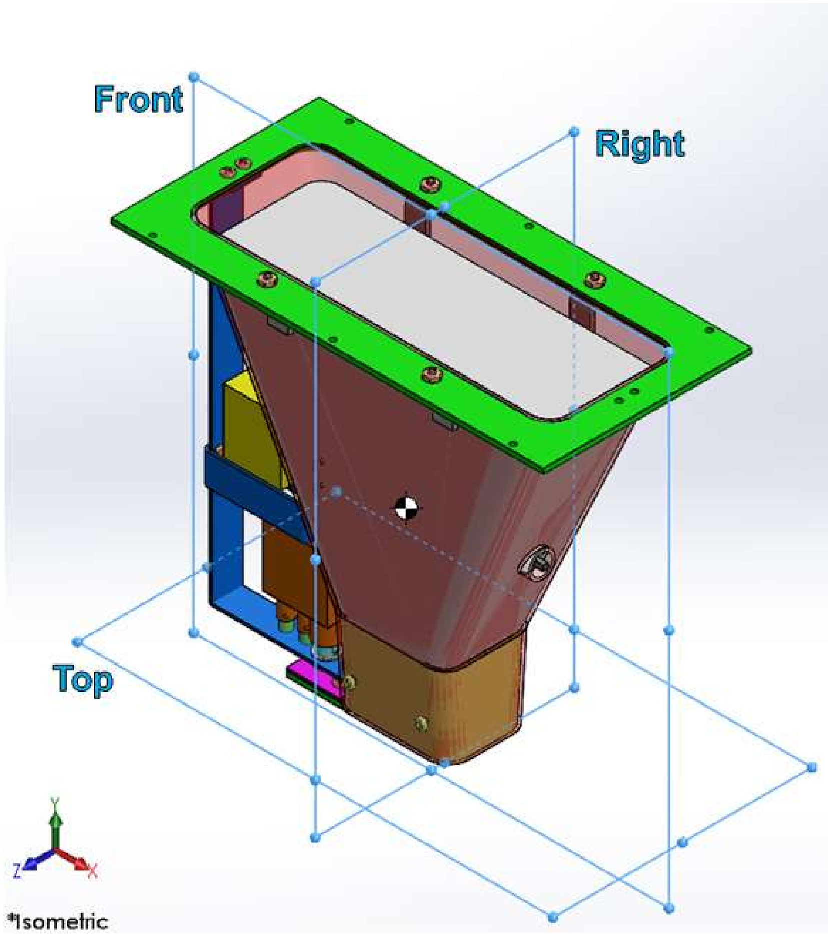

Figure 50. Granular mechanism center of mass and origin.

Figure 51 shows the mechanism's center of mass in its initial state, fully loaded with granular salt. This figure is included to provide a visual perspective for the center of mass coordinates of the initial state. In each view of Figure 51, the center of mass is indicated by a red arrow.

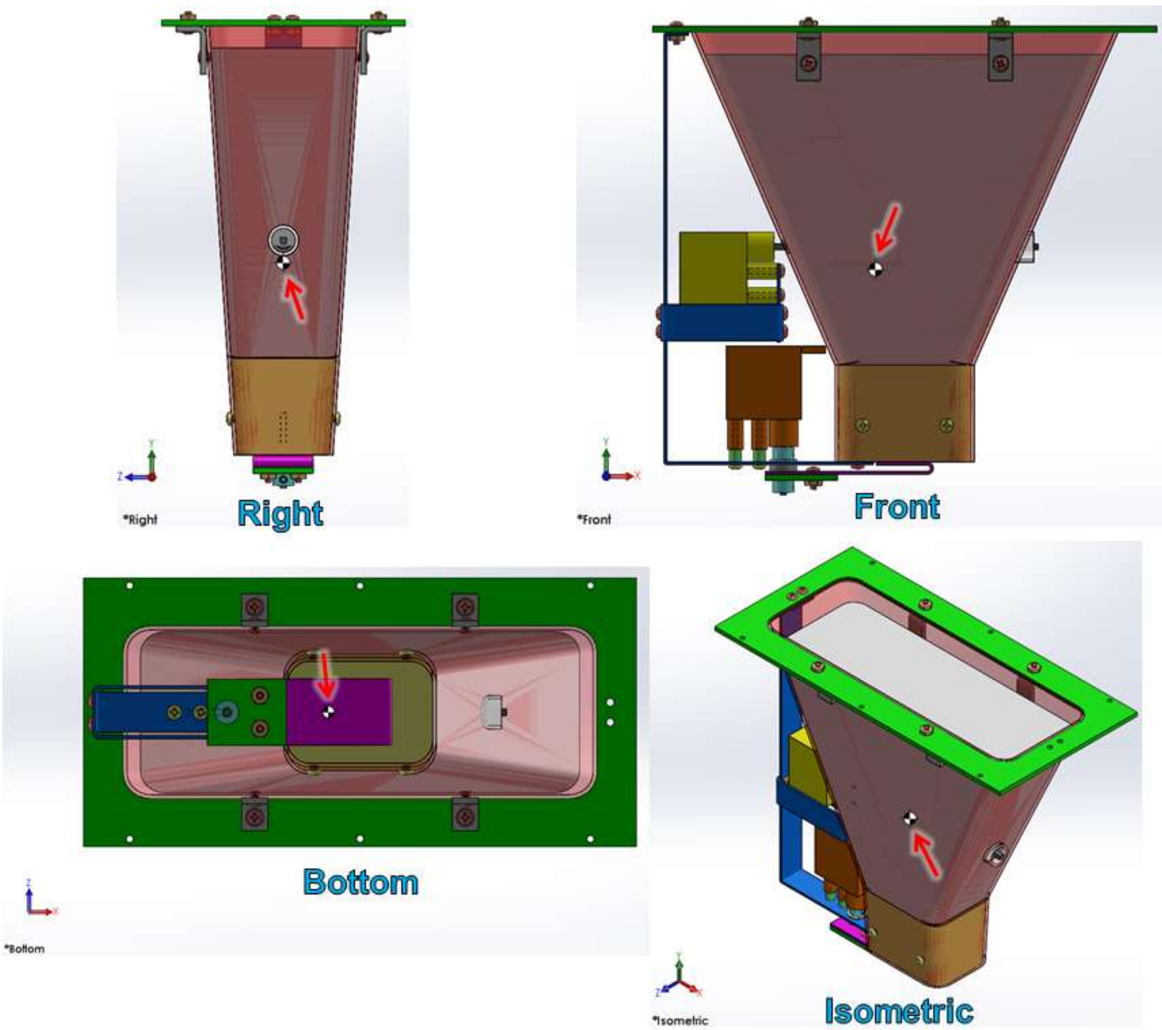

Figure 51. Granular mechanism center of mass, as seen from the right, front, bottom, and isometric perspectives.

A total of four center of mass coordinates were determined to examine how the X, Y, and Z (roll, yaw, and pitch axes, respectively) coordinates change as the mechanism goes from being fully loaded with salt, to completely empty. These center of mass coordinates can be seen in Table 6.

Table 6. Granular mechanis center of mass with respect to time.

	Roll (x) [in]	Yaw (y) [in]	Pitch (z) [in]	Comments
State 1 (Fully Loaded, Door Closed)	-0.60127	3.97137	-0.00009	
State 2 (Fully Loaded, Door Open)	-1.3293	-0.18021	1.20495	
Change from 1-2	-0.72803	-4.15158	**1.20504**	**Largest change in position from State 1**
State 2 (Fully Loaded, Door Open)	-1.3293	-0.18021	1.20495	
State 3 (Empty, Door Open)	-0.91242	4.16173	0.03399	
Change from 2-3	0.41688	4.34194	-1.17096	
Change from 1-3	-0.31115	0.19036	0.03408	
State 3 (Empty, Door Open)	-0.91242	4.16173	0.03399	
State 4 (Empty, Door Closed)	-0.82747	-0.18021	-0.00212	
Change from 3-4	0.08495	-4.34194	-0.03611	
Change from 1-4	-0.2262	-4.15158	-0.00203	

The mechanism’s center of mass shifts a maximum of 1.20504in along the pitch axis. It is important to realize, however, that this relatively large displacement (compared to the preferred maximum displacement of 0.5in along the pitch axis) occurs only when the mechanism is fully loaded with the door open; assuming the salt does not jam, this is merely an instant in time. As the salt begins to flow, the center of mass will immediately start moving toward the center of the mechanism along the pitch axis. Also, at the instant when the mechanism is fully loaded with the door open, the multirotor will be either hovering or operating at a very low speed along the length of an ice dam, and therefore, potential rotation about the roll axis (caused by a shift along the pitch axis) will not significantly affect the stability of the multirotor operation.

It is most important that the center of mass along the pitch axis remains closer than 0.5in from the center of the mechanism when the multirotor is flying from ground level to the ice dam (corresponding to State 1) and when it is flying from the ice dam to ground level (corresponding to State 4). In these two states, the mechanism has pitch-axis center of mass positions of -0.00009in and -0.00212in, respectively; both of these values are well within the desired 0.5in range.

7.6.9 Overall Mass and Height Check of the Final Design

The overall masses of the fully-loaded and empty mechanism were determined using both SolidWorks and the actual granular mechanism prototype. Table 7 presents the mass of each individual component of the mechanism as determined with SolidWorks, along with the total mass of the mechanism with and without a full load of granular salt.

Table 7. Granular mechanism mass breakdown.

GRANULAR MECHANISM	TOTAL MASS (kg)
Mechanism Part	
Mounting Plate	0.05877
Frame Piece 1	0.02808
Frame Piece 2 (x2 Total) (Labeled as 2 and 3 in report)	0.01362
Frame Piece 3 (Labeled as 4 in report)	0.00311
Agitator	0.01049
Swivel Release Door	0.01647
5/8 x 1 304 SST Mounting Bracket (x2 Total)	0.0204
Square Shaft Stock (Accounts for Both Shafts)	0.01178
Double Sealed Bearing	0.00376
Nylon Sleeve	0.00124
#6-32 x 3/8" Screw (x18 Total)	0.01782
#6-32 x 3/4" Screw (x6 Total)	0.00918
3/16" ID Shaft Collar (x3 Total)	0.00411
PTFE Washer (x4 Total)	0.00148
Gutter Funnel	0.133
3D-Printed Funnel Outlet Reducer	0.16107
Vex Servo	0.048
Vex 269 Motor	0.073
Swivel Release Door Hub	0.00447
TOTAL	**0.61985**
Full Load of Granular Salt (48 oz of Magnesium Chloride)	1.239
Loaded Total	**1.85885**

The fully-loaded mechanism has a mass of 1.85885kg. This total mass is well below the 2.5kg payload capacity, allowing for a 0.64115kg margin for the to-be-designed means of mounting the electronics to the mechanism, and for mounting the mechanism to the multirotor.

The mass of the actual prototype, with electronics attached (discussed later) is 0.572kg empty, and 1.811kg filled. The original goal of 0.7kg of salt was exceeded by 0.539kg.

The granular deployment mechanism has an overall eight of 10.25in, which is 0.75in below the 11in height constraint. Figures 52-54 show the completed first generation granular mechanism prototype, both empty and with a full load of granular salt.

Figure 52. Fully-loaded granular mechanism prototype.

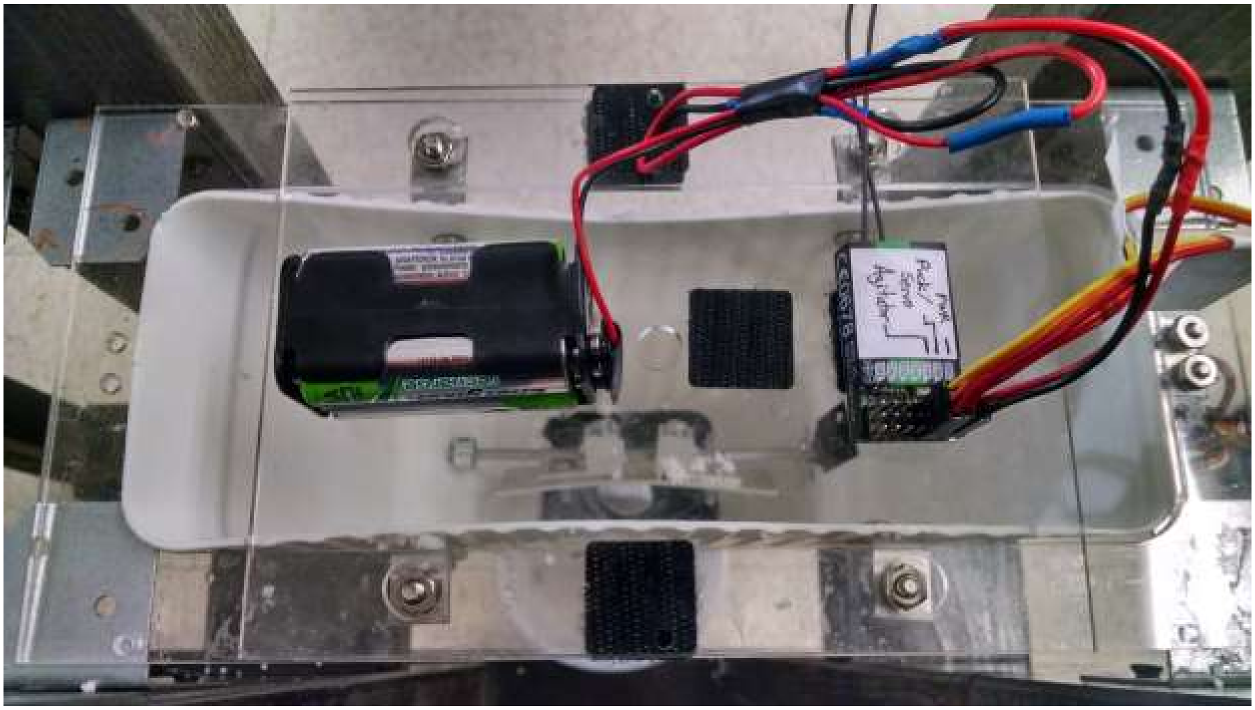

Figure 53. Empty granular mechanism prototype, with electronics plate attached, on the test stand.

Figure 54. Granular mechanism prototype motor mounting.

7.7 Electronics and Control

7.7.1 Electronics Overview

The only necessary electronics needed to drive the mechanisms' motors are a battery pack and a receiver with enough free channels to power a maximum of two motors (the granular mechanism has two motors, while the puck mechanism has only one; only one mechanism is mounted at a time). It is recommended that future projects incorporate the electronics package and the mechanism mounts into one static package. Lack of regular physical access to the multirotor resulted in the simpler-to-design arrangement described here.

The easiest way to mount the electronics plate to the puck mechanism and funnel mechanism mount plates was determined to be small squares of adhesive-backed hook-and-loop fastener. The receiver and battery pack are affixed to this plate with hook-and-loop fastener as well, to aid in battery recharging efforts. Originally, the intent was to affix the electronics plate to the mount plates with clevis pins. However, hook-and-loop is faster to remove/replace when reloading either mechanism.

Inclusion of a camera system with this electronics package would allow for relative precision in the dropping of the salt from each mechanism; due to constraints alluded to earlier with regards to multirotor access, line-of-sight must be used instead. Appendix A includes the camera equipment that would have been incorporated.

The Robotics Engineering MQP, using the DJI S1000+, is known to be using a 5.8GHz transmitter/receiver combination for flight control. With this in mind, a 2.4GHz separate transmitter/receiver combination is used for the salt deployment system in order to reduce the probability of interference, while simultaneously allowing control over the mechanisms independent of the flight controls. The Flysky FS-iA6 [60] with a paired 6-channel receiver is ideal for this application. The electronics package and transmitter are pictured in Figure 55.

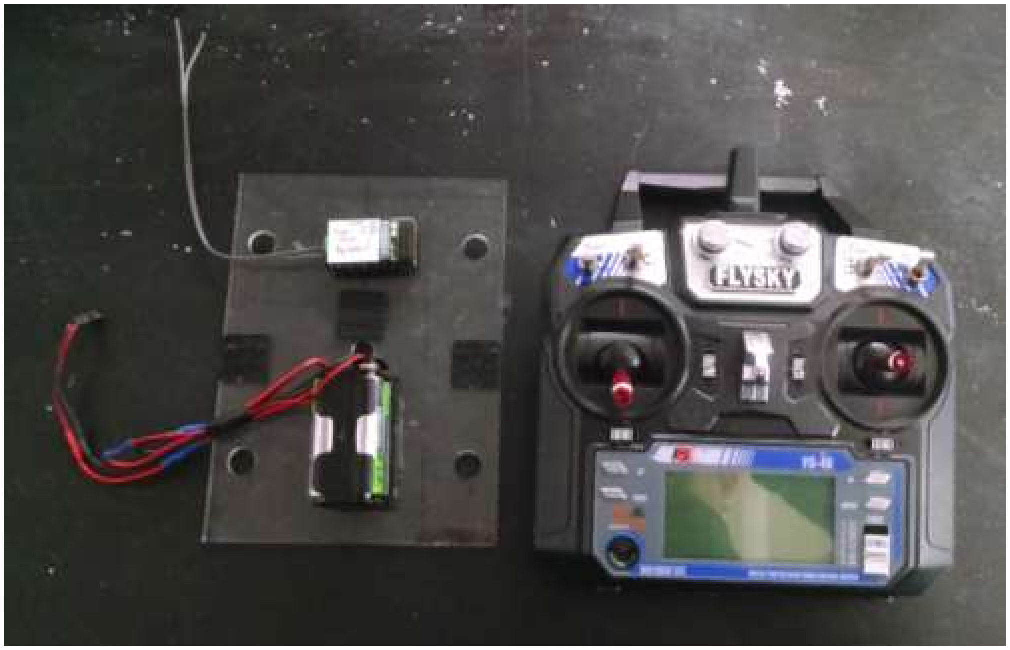

Figure 55. FlySky FS-iA6 transmitter and electronics plate.

7.7.2 Masses and Dimensions of the Electronics

Keeping the 2.5kg payload capacity of the multirotor in mind, it was important to determine the mass of the battery pack and receiver, which would be common to both mechanisms. The general term “electronics” shall comprise the battery pack and receiver. The masses are shown below.

Mass of Battery Pack (4x AA): *0.104kg*
Mass of Receiver: *0.007kg*
Mass of Electronics Plate: 0.08kg
Total Mass of Electronics**: 0.191kg**

This mass is small enough to be considered within the 1kg factor of safety, which comprises the driving electronics for each mechanism and any additional mass that the multirotor may need to operate, such as a bigger battery or accessories. This mass does not include the motor(s) used in each mechanism, which are instead part of the total mechanism masses.

The receiver and battery pack are compact in size. The battery pack measures 6.5cm long, 3.2cm wide, and 3.2cm high. The receiver is 4.2cm long, 2.5cm wide, and 1.5cm high.

7.7.3 Power

The 5th and 6th transmitter channels are used for multirotor operation, due to convenience of pairing the switches to these channels and their physical proximity to the power connector for easy wiring on the receiver. The 6-channel receiver actually has seven connectors, one of which is power (the top one in Figure 56). Ground is the furthest-right pin, while power is the middle pin. The furthest-left pin is reserved for signal, but this pin is not required when wiring the battery to the receiver. It is imperative to remember this wiring scheme when connecting the motors to the receiver.

Figure 56. Receiver, with label attached. Vertically: Power connector, Ch6, Ch5, Ch4, Ch3, Ch2, Ch1.

A 4x AA battery pack with a square cross-section is used, and it is from here that the receiver is provided with 6V of power (1.5V per battery). The receiver can handle from 4.0-6.5V DC according to the user manual. The capacity of each battery is 1300mAh, for a total of 5200mAh (5.2Ah). The VEX motors mentioned previously have specifications listed at 7.2V DC, but 6V maintains receiver compatibility. Lower voltage supply to the motors slightly reduces their specified capabilities.

The VEX 393 motor, used to operate the puck mechanism, has a free current draw of 0.37A and a stall current of 4.8A [58]. The VEX 269 motor used in the funnel mechanism has a free current draw of 0.18A and a stall current of 2.6A, while its VEX servo draws up to 1.5A [59]. The VEX 393 motor has the highest power demand of any of the motors.

The puck mechanism VEX 393 motor at stall provides the shortest running time. Dividing the battery capacity (5.2Ah) by the stall current draw (4.8A) yields 65 minutes of run time at stall. Similarly, the VEX 269 could run for 2 hours at stall current, and the servo could run for 3.47 hours at max current draw.

7.7.4 Description of VEX Motors

The VEX motors themselves are Direct Current. The 393 and 269 are two-wire motors, requiring a motor controller to convert to a 3-pin arrangement of signal (white), power (orange), and ground (black). These are connected to extension cords, in a 3-pin arrangement of signal (yellow), power (orange), and ground (red).

Motor torque is inversely proportional to speed, and directly proportional to current draw. A motor driven at high angular velocity provides less torque and draws less current, while a motor that is providing torque has higher current draw and lower angular velocity.

VEX 393 and 269 Motors

Both of these models have a free speed of 100 RPM. When connected to the receiver with a 3-pin output motor controller, these motors operate on a 0-100% proportional control; 0% does not drive the motor, while 100% drives it full speed (100 RPM) in one direction, and values in between drive it at a fraction of full speed. Paired with a transmitter, the channels driving these motors can be programmed to run in forward or reverse at whatever fraction of full speed is desired.

VEX Servo

Servos differ from motors in that they contain a potentiometer, used to help accurately control position. In general, servos do not spin multiple revolutions. Instead, a signal provides the impetus for the servo to hold one specific position. Hence an input of 0-100% controls at what position the servo holds, rather than the speed it rotates (as a motor would do). The desired position is largely dependent on the orientation of the object connected to this servo, since the VEX servo cannot rotate through more than 100 degrees or so. One end of this motion corresponds to 0%, while the other end corresponds to 100%.

The salt release door is mounted somewhere in the middle of the 0-100% scale. An input causes the servo to match a different position (the open position) allowing salt to fall; a different input causes the servo to match its starting position (the closed position).

7.7.5 Transmitter Function Mapping

The receiver has six channels plus one power input, while the transmitter has many more inputs. Four of the channels are conventionally reserved for movement (in the case of a multirotor, throttle up/down, yaw left/right, tilt forward/back, and tilt left/right), with the four requisite connections wired directly from the flight controller. Independence from the multirotor flight controls results in all six channels being available.

The two joysticks encompass four of these channels out-of-the-box. The four switches (three of which are two-position switches, the last one being a three-position switch) and two proportional control knobs may all be used for either mode switching operations or as the fifth and sixth channels.

The FS-i6 AFHDS transmitter can be programmed to change the input method for channels 5 and 6. It can also be used to change the endpoints of motion for all channels, taking a 0-100% input for both ends of motion for each channel. In fact, the adjustment can be made up to 120%, which is presumably an option to run the model airplanes it was designed for at some turbo setting.

Switches A, C and D are used between the two mechanisms, mapped under two different “Models” on the transmitter. These models allow for different programs to be loaded and modified. The switches were used because the knobs, while good at proportional control, have disadvantages. The primary disadvantage is that they cannot control both forward and reverse motion without the “stop” position being somewhere in the middle of their rotation, and there is no instantly-recognizable visual or tactile feedback that the knob is in its middle position. This makes manual control infeasible.

Figure 57. Transmitter buttons and knobs, with labels attached. Left to right: Switch A, Switch B, Knob A, Knob B, Switch C, Switch D.

The MQP_PUCK model uses Channel 6, mapped to Switch C (second from the right in Figure 57), to control the puck mechanism motor. This is the three-position switch, chosen to allow for easier reloading operations. The Down position cycles the mechanism forward, while the Up position cycles it backwards. This was chosen due to how the transmitter is usually held, with one or both hands on the back of the unit. It is easier to flip the switch up to its middle position to turn the puck motor off, than it is to pull the switch down. This method is efficient given that the Up position is seldom used (only when reloading or when a small jam is present).

The MQP_GRAN model uses Channels 5 and 6, mapped to Switches D and A, respectively. Switch D (Channel 5) controls the less important of the two operations for the granular mechanism: the agitator. This device is seldom used but important in case of a clog. It uses a two-position switch that controls the On (Down, full forward in one direction) and Off (Up) states. Switch A (Channel 6) controls the salt release door servo. The Up position closes the door, while the Down position opens it. Both arrangements were chosen for the same reason discussed above for the puck mechanism: it appears easiest and quickest to flip a switch “up” to turn off an actuator or close a door, i.e. the “Kill” conditions.

Simple labels on the transmitter, receiver, and motor wires were placed to aid in the rapid switching of mechanisms.

7.7.6 Transmitter Programming

The transmitter is very simple to use, and comes pre-paired to its receiver out of the box. To turn the unit on, the throttle must be in its full-down position and all switches must be in the Up position. Most of the switch mapping was done with the latter fact in mind, with Stop being the Up position (this is only violated by the puck mechanism, which must go in both forward and reverse). Long-pressing the OK button near the screen on the bottom of the unit brings up the menu. Navigating to the System Setup menu with the Up and Down keys allows selection of a model, of which there are two: MQP_PUCK and MQP_GRAN. Long-pressing Cancel confirms the selection, and pressing Cancel again goes back to the main menu.

The selected model may be programmed by instead navigating to the Functions Setup menu after long-pressing the OK button. Here, channels may be “Reversed,” “End points” (0-100% for both ends of motion) may be programmed, and “Aux. channels” may be used to set the switches or knobs for channels 5 and 6, among other things. In all menus, OK selects an option, Cancel goes back, and long-pressing Cancel confirms a selection.

End points are the only tricky aspects to set, in that they require significant trial-and error to get correct; in addition, the switch or knob in question must be in the position for which programming is to be accomplished. If a motor being On in the Down position is desired, the switch must be in its Down position in order to access the ability to change its respective End point. Similarly, it must be in its Up position to change its End point (e.g. to 0% “Stop”). From a hardware standpoint, one must be very careful to not break the motors or mechanism while programming the transmitter, as these motors will run while being programmed.

8.0 Testing

A number of ground tests were performed in order to confirm reliable mechanism operation. These tests included a Load and Drop test, as well as a Range test. Airborne tests were initially planned to be completed as well, but this may be explored further in D-Term, when a multirotor is more readily available.

A test stand - made of 2x4 wood pieces, brackets, and screws- was made to hold both mechanisms, similar to how the mount tabs would hold them to the underside of a multirotor. This stand is shown in Figure 58.

Figure 58. Puck and granular mechanisms mounted to test stand.

8.1 Load and Drop Test

The purpose of this test is to verify that the pucks and granular salt can be loaded and deployed in a timely fashion under user control. This test also serves to find the amount of time required by each mechanism to drop its full salt load.

Puck Mechanism

Loading the Mechanism

- Remove the mechanism from the mechanism stand.
- Remove the mount plate from the mechanism.
- Use custom-made “loading tool” to block the puck outlet area, preventing pucks from dropping from the mechanism.
- Load pucks from the top of the mechanism, gradually cycling the spinner plate in the clockwise direction such that four pucks can ultimately drop into their positions on the first layer.
- When the four pucks have been loaded, cycle the spinner such that one of the pucks covers approximately half of the Puck outlet hole. This will prevent a puck from falling prematurely when the loading tool is removed.
- Continue to load pucks from the top of the mechanism, filling the spinner plate in the upper layer with three pucks.
- Remove the loading tool from the puck outlet area.
- Replace mount plate.
- Place the collector bucket beneath the mechanism drop hole.

Testing the Puck Mechanism

- A total of 10 trials shall be completed. Each trial involves loading the mechanism with 7 pucks, and then releasing the pucks into the bucket, as described in the previous two sections.
- The operator is to stand far enough away that he cannot see the operation of the mechanism - only the pucks falling out of it.
- For each trial:
    - Record the amount of time required to load the mechanism.
    - Record the amount of time required to drop all 7 pucks from the mechanism.
    - Record whether or not the mechanism jammed, and what was done to clear the jam (putting an emphasis on methods that do NOT require physical interaction with the device).
- The mechanism is determined to be successful if at least 8 out of the 10 trials are completed without jamming that requires physical interaction with the mechanism.

Granular Mechanism

Loading the Mechanism

- Mount the mechanism on the mechanism stand and ensure that the swivel release door is closed (blocking the funnel outlet).
- Place the collector bucket beneath the mechanism.
- Remove the electronics plate from the mechanism.
- Pour granular salt into the mechanism via the top opening, stopping when the salt level is approximately in-line with the top bracket screws inside the funnel.
- Replace the electronics plate.

Testing the Mechanism

- A total of 10 trials shall be completed, 5 fry and 5 wet. Each trial involves loading the mechanism with granular salt and then releasing it into the bucket.
- The operator is to stand far enough away that he cannot see the operation of the mechanism - only the salt falling out of it.
- For each trial:
    - Dry Testing
        - Reload as described above, recording the time to do so.
        - Open the swivel release door so that salt begins to flow out the bottom of the mechanism and into the collector bucket.
        - Open/close the release door twice per trial, studying the interaction between the falling salt and the door.
        - Once all salt has poured from the mechanism and into the collector bucket, close the swivel release door.
    - Wet Testing
        - Reload as described above, but before loading the mechanism, wipe the inside surfaces of the mechanism with a wet paper towel. After loading, moisten the top layer of salt with a wet paper towel.
        - Open the swivel release door so that salt begins to flow out the bottom of the mechanism and into the collector bucket.
        - Upon opening of the release door, if salt does not flow or appears hindered, turn on the agitator. Do NOT operate the agitator unless the swivel release door is opened to prevent breaking the motor.
        - If the agitator does not promote salt flow, turn off the agitator and close the release door.
        - Once all salt has poured from the mechanism and into the collector bucket, turn off the agitator and close the swivel release door.
    - Record the amount of time required to release all salt the from the mechanism for the Dry Test.
    - Record the amount of time required to release all salt from the mechanism for the Wet Test.

    - Record whether or not the agitator was needed to promote salt flow, and whether or not it was successful at doing so.
- The mechanism is determined to be successful if at least 4 out of the 5 trials in both the dry and wet portions of testing are completed without jamming that requires physical interaction with the mechanism.

8.2 Range Test

The purpose of this test is to determine the maximum range at which the transmitter/receiver will work for each mechanism. Seeing as the receiver will be located at approximately the same location on each mechanism (due to the common electronics mounting plate used by each), only the puck deployment mechanism will be used for this testing.

Signal interference between a transmitter and receiver is likely to be much higher at ground level in a grass and tree-surrounded environment, than it will be between ground level and a roof. Operating the mechanisms around houses/roofs will likely provide the only main signal interference when used for the intended purpose, besides that introduced by trees, grass, plants, etc.

With this in mind, the mechanisms' transmitter and receiver will be tested at ground level in Institute Park and the surrounding area in order to simulate a "worst-case" interference scenario, and to determine the maximum range at which the transmitter and receiver can communicate under such conditions. The WPI football field and surrounding streets will also be utilized, over which Google Maps may be used to easily gauge distances. Most test distances will be much greater than those encountered while clearing a roof. This is especially true when considering the maximum line-of-sight distance from which one would be able to see salt fall from the mechanisms.

This test will also serve to determine whether the transmitter signal requires line-of-sight with the receiver in order for a clean signal.

9.0 Results

9.1 Load and Drop Test Results

Puck Mechanism

Table 8. Puck mechanism load/drop test results.

Trial	Load Time	Drop Time	Jammed?	Comments
1	3:46	0:23	Slight	Still worked - see below
2	2:31	0:14	No	Flawless
3	1:52	0:17	No	Flawless
4	1:19	0:17	Slight	Still worked - see below
5	1:20	0:14	Slight	Still worked - see below
6	1:30	0:15	Slight	Still worked - see below
7	1:22	0:11	No	Flawless
8	1:31	0:12	Slight	Still worked - see below
9	1:12	0:08	No	Flawless
10	1:24	0:11	Slight	Still worked - see below
AVG	**1:46.7**	**0:14.2**	6/10 trials	All 6 jams were successfully cleared

Average times were obtained with a calculator [62]. Test results are shown in Table 8.

The average time to load was under two minutes. Note that the times improved with practice. Once the trick to reloading was perfected, times decreased from almost 4 minutes in the first test to less than 1 ½ minutes in the last.

The original criterion for a “successful” mechanism was for the mechanism to function without requiring physical intervention. Considering this, the mechanism was a success.

Despite efforts to prevent jamming, second-layer pucks frequently landed on the first-layer spinner, causing slight jamming. However, every time this occurred, the operator could tell because the cycle time between puck drops was very low. Note the average drop time of 14.2 seconds; this corresponds to seven pucks dropped, one puck every two seconds. If a puck does not fall within four or five seconds, this is a clue to the operator that a slight jam has occurred.

All six jams encountered during testing were resolved by cycling the item in reverse slightly (to "shake" the puck off the first-layer spinner and into place).

The device did not work "flawlessly" 8/10 times, but it did work all ten times without requiring physical intervention from the testers. Therefore, the mechanism was deemed "successful," albeit in need of improvement.

Granular Mechanism

Table 9. Granular mechanism load/drop test results.

Trial	Load Time (Dry)	Drop Time (Dry)	Drop Time (Wet)	Wet Test Jammed?	Comments
1	0:34	0:18	0:16	Yes	Worked with agitator use
2	0:38	0:18	0:14	No	Flawless
3	0:23	0:19	0:14	No	Flawless
4	0:22	0:18	0:13	No	Flawless
5	0:21	0:18	0:13	No	Flawless
AVG	**0:27.6**	**0:18.2**	**0:14**	1/10 trials	The only jam was cleared with agitator use

Test results are shown above in Table 9.

The load times here a much shorter than for the puck mechanism, alluding to the relative ease with which salt may be simply poured in. Some of the time was due to the need to remove and replace the electronics plate, but this was otherwise a quick process.

Drop times were rather quick, without sacrificing control. In one test, 48 oz. (1.239kg) of salt was dropped in 18.37 seconds, resulting in a mass flow of approximately 0.0674kg/s. The opening and closing of the salt release door was quick and error-free; the salt had a straight flow with minor dispersion through the 2ft or so it fell from the test stand.

One problem was encountered during wet testing. Salt falls through the 3D printed diameter reducer, which is shaped like a funnel with a constant-diameter neck. This neck was originally 1in wide and just over 1in high vertically. Salt was jamming such that when the swivel release door was opened, salt did not flow at all. In the final design, this 1in-diameter neck was reduced to a height of 0.25in, resulting in a much steeper slope through which salt could flow more freely.

The new version of the diameter reducer is shown in Figure 59, which is a bottom-view of the component. Note the very small length of the neck, extending up into the mechanism from the circular hole; this is the portion that previously caused jams with its approximately 1in long dimension. After inserting the new component, testing went smoothly. The only jam encountered following this modification was successfully cleared with agitator use. Running the agitator at the same time that the swivel release door is initially opened may preempt any jamming.

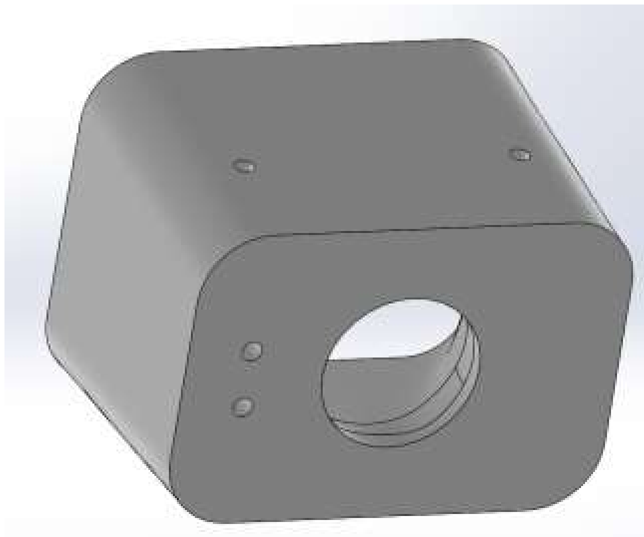

Figure 59. Granular mechanism funnel outlet diameter reducer, bottom view.

9.2 Range Test Results

A total of six range tests were run to determine the effective range of the transmitter/receiver combo. As described previously, only the puck mechanism was used during this test, since the receiver is similarly exposed when mounted to either mechanism. Testing was run over the maximum local line-of-sight distances that could be found around WPI, as described below.

The first test was conducted on the WPI football field, using the 100m markers on the adjacent track. This distance is the furthest that the operator can be from the mechanism while being able to effectively see the falling salt. In Figure 60, one group member held the mechanism, while another (background) operated it with the transmitter from 100m away.

Figure 60. Range test, with operator standing 100m away at the red arrow.

Next, a test was run diagonally across the football field, at a distance of approximately 120m. In Figure 61, this is shown with a red line. With this test successful, the transmitter operator walked in a straight line from the football field to Salisbury Street; contact was lost 338m from the mechanism, when the tester stepped behind a small rise. This test reinforced the fact that the transmitter must be in a line of sight with the receiver to work.

Salisbury Street itself was used for the next test. From the hill at Goddard Laboratories to the intersection of Lancaster and Salisbury is a distance of 432m (the orange line), over which the mechanism worked flawlessly. Nearby Institute Park provided more space, where tests from Goddard Laboratories to a small structure in the park (purple line, 277m), and again from this structure to the hill near Faraday Hall (green line, 467m) both succeeded. The latter was the farthest unobstructed test distance.

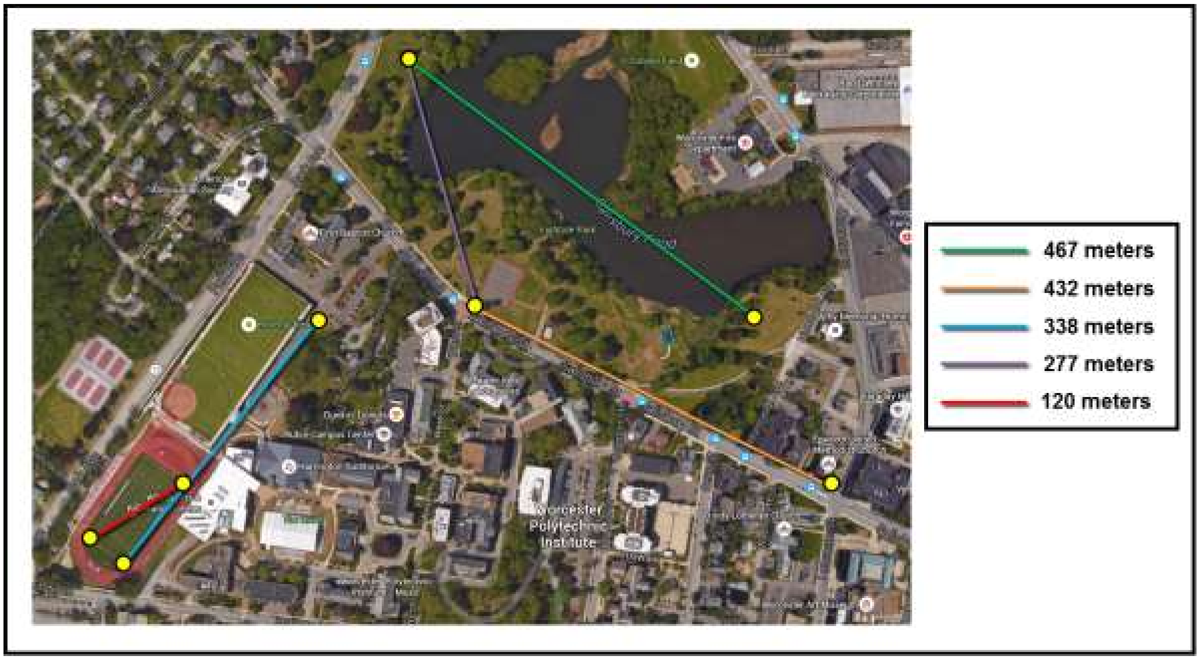

Figure 61. Overhead view of range test distances and locations around the WPI campus.

In conclusion, the system can work at a distance of at least 467m line-of-sight. Seeing as a maximum distance of approximately 100m is anticipated in actual ground-to-roof usage with a multirotor, the 467m line-of-sight maximum distance is sufficient.

10.0 Conclusions

Noticing the lack of affordable and reliable ice dam mitigation technologies, emerging UAS technology was used to help solve the problem of precision ice-melt deployment. As the popularity of enthusiast drones like the DJI Phantom and concepts such as Amazon Prime Air shows, this technology may have a myriad of unexplored applications, such as the one first explored here. The emphasis on use of a commercially-available drone is perhaps indicative of the potential this industry has yet to explore.

Focus was placed on the development of a standard mounting and payload system for at least one multirotor model, in order to drop salt pucks and granular ice melting salt onto winter roofs. A number of existing solutions (ranging from the inexpensive to the inadvisable) were explored, and cost-efficient mitigation of pre-existing ice dams was an area found to be lacking. Improvement of the process of throwing salt onto roofs (which is imprecise or damaging) was of greatest concern.

A number of multirotor payload designs were conceptualized to solve this problem. Two separate designs were iterated upon to drop the two different physical formats of salt. In an application prone to occasional crashes or collisions, the use of rapid prototyping technologies was emphasized in order to quickly manufacture or repair the mechanisms.

The result was two lightweight mechanisms capable of being transported by the DJI S900 or S1000+ multirotor models. The puck deployment mechanism carries seven pucks (0.7kg) of Roofmelt ice pucks, while the granular deployment mechanism carries 1.239kg of pet-safe ice melt, both of which are available at area hardware stores.

Each mechanism implements a common mounting situation and power/control system independent of the multirotor flight systems. They rely upon manual line-of-sight operation for the time being, due to the lack of access that this project had to a multirotor. Regardless, the first generation prototype of each mechanism functioned sufficiently without requiring physical intervention. All jams were clearable remotely. Short payload deployment times and relative ease of reloading for both mechanisms make the entire operation process efficient for skilled operators. Several improvements must be made to enhance functionality and operation of the mechanisms.

10.1 Recommendations

The granular mechanism was the more reliable of the two mechanisms, owing to its relative simplicity. Operation could be streamlined by incorporating a “ball valve” release within the bottom of the funnel, as opposed to a swiveling door. This would eliminate bending moments inherent to the current design due to the weight of granular salt that is in contact with the door. Alternatively, a guide at the point farthest from the door’s axle could be implemented to ease these moments by prohibiting the door from bending.

The agitator of this mechanism could also be converted to a vertical arrangement, such that the end of the agitator would rest directly above or within the outlet of the diameter reducer. This could be achieved by carefully modifying the electronics and mounting locations, and would allow granular salt to be more effectively stirred and made to flow out of the funnel in the event of a jam. Additionally, the agitator could be composed of a corkscrew or auger-shaped component instead of a flat, rectangular panel, in order to better-promote flow and reduce strain on the agitator motor.

Initial ideation for the puck deployment mechanism led to a number of ideas using vertical puck tubes, for ease of loading and small form factor. It is anticipated that a vertical tube arrangement would be much simpler and more compact than the current arrangement, in both operation and during the action of reloading. Manufacturability concerns led to these ideas not being prototyped, but future projects may find success in this area. The single largest drawback of the current puck mechanism is the practice required to quickly and properly reload the mechanism.

It may be possible to implement some degree of automation in the puck dropping action, or to drop a certain pre-prescribed mass of granular salt. A microcontroller such as an Arduino, interfacing between the motors and the receiver, may remove the need to manually drop pucks or granular salt. It is recommended that this option be explored by future projects, seeing as it would allow operation of the mechanisms to be much less dependent on imprecise operator input.

Lastly, to ease the reloading processes for both mechanisms, small stands (permanently-affixed, lightweight “landing legs”) could be implemented onto the body of each mechanism. This would allow the mechanisms to stand upright without needing to be placed in the mounting stand. Finally, a more extensive standard mechanism mounting plate with integrated driving electronics could be designed, as the mechanisms currently rely upon a removable electronics plate that must be interchanged between mechanisms.

10.2 Business Plan

The initial project goal was to provide very low-cost ice dam control and removal services to area households using the prototyped mechanisms. This would have granted the opportunities for the two prototypes and overall system to be tested on ice-dam-affected homes, while using revenue to recoup some of the costs of the components used. Such a business plan calls into question a number of liability and legality concerns, especially with respect to the commercial operation of a UAS, as discussed in Section 3.3.6. For this reason, this plan was determined to be infeasible for this project. Even if the legal concerns had been addressed and worked with, the 2015-2016 winter season did not provide sufficient snowfall for the formation of significant ice dams, and therefore, it is unlikely that this plan could have been carried out.

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Appendix A - Multirotor Components List for S1000+

The Robotics Engineering MQP, also running during the 2015-16 academic year, obtained a DJI S1000+ multirotor. They decided upon the following list of components to complete the system. Special thanks to Gregory Tighe for providing this list.

Table 10. Robotics Engineering department MQP S1000+ components list.

Seller	Description	Number	Cost($)	Subtotal	Rationale	Source
DJI	DJI S1000 Multirotor	1	1900	1900	Desired Platform for both project teams	http://store.dji.com/product/spreading-wings-s1000-plus
3DR	Pixhawk	1	200	200	Main control board	https://store.3drobotics.com/products/3dr-pixhawk
	Compass/ GPS	1	90	90	Required for autonomous or assisted flight	https://store.3drobotics.com/products/3dr-gps-ublox-with-compass
	PPM Encoder	1	25	25	Required depending on radio choice, either way something we should buy just in case	https://store.3drobotics.com/products/ppm-encoder
	Telem Radio	1	100	100	Required for base station comms	https://store.3drobotics.com/products/3dr-radio-set
	Buzzer	1	8	8	Not essential but required for safety	https://store.3drobotics.com/products/buzzer-for-px4

	Ext. USB/LED	1	20	20	Not essential but required for safety	https://store.3drobotics.com/products/pixhawk-peripheral-kit
	Airspeed Kit	1	55	55	Not required but will be very useful	https://store.3drobotics.com/products/pixhawk-airspeed-sensor-kit
	Radio Set	1	200	200	Should be directly compatible with the Pixhawk and avoids Hobbyking shipping	https://store.3drobotics.com/products/rtf-flysky-fs-th9x-rc
	Video Link	1	200	200	A video fpv link that allows the user to see the what the quadrotor does	https://store.3drobotics.com/products/3dr-fpv-osd-kit
Amazon	Charger	2	55	110	Different seller, this should be a fine charger and doesn't come from hobby king	http://www.amazon.com/gp/product/B00466PKE0/ref=s9_simh_gw_p236_d0_i2?pf_rd_m=ATVPDKIKX0DER&pf_rd_s=desktop-1&pf_rd_r=16RG04F34K85W5MKCSE7&pf_rd_t=36701&pf_rd_p=2079475242&pf_rd_i=desktop
	Battery Alarm	1	10	10	Sounds alarm when lipo	http://www.amazon.com/Venom-

					reaches dangerous state, some flight controllers have this built in but it never hurts to have lots of backups, and there lots of very cheap options	Voltage-Monitor-LiPO-Batteries/dp/B0064SHG0Y
	Display	1	25	25	A screen to display the camera feed on	http://www.amazon.com/Leegoal-RearView-Headrest-Monitor-Rotating/dp/B007SLDF7O/ref=sr_1_3?ie=UTF8&qid=1446147521&sr=8-3&keywords=car+rearview+monitor
	Case	1	350	350	Should be just big enough	http://www.amazon.com/Pelican-0370-Cube-Camera-Black/dp/B004AHLPCG/ref=sr_1_1?ie=UTF8&qid=1446529171&sr=8-1&keywords=pelican+0370
	Battery	3	200	600	Not super nice but should be fine for us	http://www.amazon.com/gp/product/B00Z4TAMHS/ref=s9_simh_gw_p469_d0_i1?

						pf_rd_m=ATVPDKIKX0DER&pf_rd_s=desktop-7&pf_rd_r=0TS03TN2YQA97GVGMFTQ&pf_rd_t=36701&pf_rd_p=2253156982&pf_rd_i=desktop
Helipal	Extra Props	1	100	100	Probably not necessary and the site is super sketchy (we bought them anyway)	http://www.helipal.com/s1000-premium-25-dji-s1000-propeller-pack-8.html
			TOTAL (no shipping)	3993		

The following modified list of components uses many of the same ones as above, with cost-saving measures to reflect this project's differing goals and budgetary restraints:

Table 11. Modified S1000+ components list.

	Name	Link	Qty	Cost Per	Price	Description
Multirotor	DJI Spreading Wings S1000+	DJI	1	1900	1900	Octocopter. 4.4kg. Max takeoff is 11kg.
Essential Accessories	DJI Naza-M V2	DJI	1	299	299	Flight controller
	Tenergy TB6-B	Amazon	1	55.99	55.99	Charger w/Power supply. Same as RBE MQP
	16000mAh 6S 25C LiPo Battery	Amazon	2	199.99	399.98	Batteries. Same as RBE MQP
	FlySky FS-TH9XB 9Ch Tx/Rx	Amazon	1	97.49	97.49	9Ch Tx w/ 8Ch Rx included. RBE MQP using a slightly modified model from 3DR
	Battery Wires (XT60 to bare)	Amazon	1	6.52	6.52	Connects battery to connectors included with S1000 without having to solder direct to battery (risky)
					2758.98	SUBTOTAL
Camera Equipment	FPV Tx/Rx + cables	Amazon	1	29.43	29.43	200mW system that shouldn't give us problems. Get cloverleaf (circular polarized) antennae if reception is a problem

	Camera	Amazon	1	14.97	14.97	Camera. 12V
	Screen	Amazon	1	24.37	24.37	Screen to receive camera picture
	Battery - FPV and Ground	Amazon	2	12.89	25.78	1000mAh 3S (11.1V) 20C batteries to power the multirotor camera setup and the ground station screen/receiver
	Power Connectors (Wires)	Amazon	1	8.99	8.99	Ability to splice ground station battery to both screen and receiver
					2862.52	SUBTOTAL
Misc	Extra Props	RangeVideo	1	99.99	99.99	Extra props. Might be able to ask when ordering multirotor from DJI, but DJI does not sell these
	Backup Voltage Monitor	Amazon	1	8.94	8.94	DJI Flight controller has voltage monitor on it, but this would increase safety
	Case	Amazon	1	344.08	344.08	Confirmed to fit S1000 - same as RBE MQPs
					3315.53	TOTAL PRICE

Appendix B - Interview notes, Joseph St. Germain, 02 Nov 2015

This interview was conducted at 3pm on 02 November 2015 by Mitchell Weeks.

Questions:

- Justification for our multirotor?
- Is our shopping list good? Need full list
- Ensure our choice of transmitter/receiver vs need to controls
  - Stepper motor
  - Vex motor + Servo
- Do we need additional hardware to power our actuators, or can we just use receiver (+ program on transmitter)?
- Feasibility of
  - Powered tether
  - Prop guards
    - Hexacopter
    - Adds weight
- Otherwise, need
  - 2x battery
  - Good speed charger

- Tether feasibility
  - 1000V w/low current
    - Low current - small dia wire
    - High current - lg dia wire
  - Step up → 1000V thru wire → Step down on robot
  - Step up and step down power supplies both weigh more than a battery would
  - Military uses tethers - research paper online
- Prop guard
  - Minimalistic
  - Stiff wire - coathanger

- Defense of multirotor choice
    - Build own - takes too long
    - Focus on main goals of MQP, not multirotor design
- Shopping
    - Boat winch servo
    - Control with winch?
    - Transmitter - at least 6 channels
        - Dial for servo
    - Receiver - 5V 3A power extender to power camera
    - Camera - look up basic FPV setup (Hobbyking)
    - CollabLab multirotor projects - get in contact
    - Charger - Imax B6AC v2
- (Current A)*(Time h) = (Capacity Ah, i.e. discharge rate)

Appendix C - Roofmelt Ice Puck Friction Calculations

The puck-form-factor ice melt is standard Roofmelt Ice Melt, available in New England at Home Depot (http://www.homedepot.com/p/Roofmelt-Ice-Melt-RM-65/202536089) or Lowe's (http://www.lowes.com/pd_363600-13902-12190065_0__?productId=3824269). This is a Calcium Chloride ($CaCl_2$) composition in the form of irregular 2.25in diamater, 1in height discs. An experiment was devised to find the friction between these pucks and a flat cast-acrylic sheet, across which they would slide in the final puck mechanism.

Materials:

- 2N Force Gauge
- Scale
- String
- Salt Pucks ($CaCl_2$, obtained at Lowe's in a 14lb bucket)
- Cast Acrylic Sheet
- Paper Towels
- Water

Procedure:

Dry Salt Pucks

1. Place paper towel on scale and zero it.
2. Place salt puck on scale and record mass.
3. Place salt puck flat-face-down on acrylic sheet.
4. Using force gauge, pull on salt puck and record the force reading just before salt puck begins to move (static force). Be careful not to let force gauge rest on the salt puck; rather, only the hook at the end should make contact.
5. Using force gauge, pull on salt puck and record the force reading as it moves at a constant velocity (kinetic force).
6. Wipe $CaCl_2$ dust off acrylic sheet.
7. Repeat steps 1-6 four more times.
8. Repeat steps 1-6 five times, but now use a string wrapped around the salt puck to interface with the force gauge.

Wet Salt Pucks

9. Repeat steps 1-8 ten times, but with the following changes:
    a. In step 2, lightly moisten one face of salt puck before finding mass.
    b. In step 3, place the salt puck moist-face-down on the acrylic sheet.

Calculations:
Force balance: Force gauge reading balances the friction force in both the static and kinetic cases.

F = uN
u = F/N = F/(mg)

Therefore:
u_static = F_static/(mg)
u_kinetic = F_kinetic/(mg)

Data: See Table 12.

The average salt puck mass is about **103g**.

Results:
The maximum static coefficient of friction that the motor will need to deal with is, on average, **0.32**. The maximum kinetic coefficient of friction is, on average, **0.19**.

In other words, the maximum friction force that one salt puck will encounter is

F = (u_static)(N)
F = (0.32)(0.103kg)(9.81m/s^2)
F = 0.3233376N

This force is exerted by an absolute maximum of 8 salt pucks against the turning motion of the motor. This counts both layers in the salt mechanism, and assumes each puck contacts solid acrylic with no cutouts - so this is a conservative estimate. The distance from the center of the spinner to the center of one of the puck holders on the plywood spinner is **2.0625", or 0.0523875m**. This is the lever arm of all 8 salt pucks against the turning motion of the motor.

As such, the maximum force the motor will encounter is when all 8 salt pucks are sliding against the acrylic plates, when the above friction force and lever arm is encountered by all 8 pucks.

M = (F)(r)

M_tot = (8)(F)(r)
M_tot = (8)(0.3233376N)(0.0523875m)
M_tot = 0.135511 N*m = 0.013814 kgf*cm = 19.189975 oz*in = 1.199 in*lb

NOTE: 1kgf = 9.81N

While this does not take into account friction from the turning shaft or the spinner contact areas with the collars holding them, it is a conservative estimate for 8 pucks on solid acrylic sheet (where the final design will incorporate weight-reducing grates on the bottom surface, reducing contact area). Note that this is a very small required moment.

The Vex 393 motor has a stall torque of 1.67 N*m. (http://content.vexrobotics.com/docs/instructions/276-2177-inst-0712.pdf)

Sliding Puck (i.e. the 8th puck problem):

An older design, in which an 8th puck sits on a shelf above the second row of pucks, may not be viable on a moving platform.

Assuming a puck mass of 100g, material of acrylic, and a coefficient of static friction of 0.32, it is a simple matter to calculate the angle at which sliding occurs by using theta = arctan(0.32).

The angle yielded is 17.74 degrees. Any takeoff/positioning maneuvers the multirotor undertakes before pucks are deployed will destabilize the 8th puck and send it falling prematurely. Hence this 8th puck will not be included in the final design, although the friction calculations above assume 8 pucks (making these values more conservative).

Table 12. Ice puck friction experiment data.

Dry	Sample	Mass (kg)	Static Force (N)	Kinetic Force (N)		Static Coeff	Kinetic Coeff		Average Static Coeff	Average Kinetic Coeff
w/o String	1	0.101	0.3	0.1		0.3027825718	0.1009275239			
	2	0.1	0.3	0.15		0.3058103976	0.1529051988			
	3	0.103	0.35	0.1		0.3463871817	0.0989677662			
	4	0.104	0.3	0.1		0.2940484592	0.09801615306			
	5	0.103	0.3	0.125		0.2969032986	0.1237097077		0.3091863818	0.1149052699
Using String	6	0.101	0.3	0.3		0.3027825718	0.3027825718			
	7	0.106	0.35	0.2		0.3365837709	0.1923335834			
	8	0.107	0.35	0.15		0.3334381282	0.1429020549			
	9	0.102	0.35	0.2		0.3497831345	0.1998760768			
	10	0.103	0.35	0.2		0.3463871817	0.1979355324		0.3337949574	0.2071659639
Avg		0.103				0.3214906696	0.1610356169			

Damp	Sample	Mass (kg)	Static Force (N)	Kinetic Force (N)		Static Coeff	Kinetic Coeff			
w/o String	6	0.107	0.3	0.25		0.2858041099	0.2381700916			
	7	0.101	0.3	0.15		0.3027825718	0.1513912859			
	8	0.101	0.3	0.2		0.3027825718	0.2018550479			
	9	0.103	0.25	0.2		0.2474194155	0.1979355324			
	10	0.106	0.3	0.15		0.2885003751	0.1442501875		0.2854578088	0.1867204291
Using String	1	0.102	0.25	0.2		0.249845096	0.1998760768			
	2	0.103	0.4	0.2		0.3958710648	0.1979355324		0.2758265991	0.1968335904
	3	0.104	0.25	0.2		0.2450403827	0.1960323061			
	4	0.102	0.2	0.15		0.1998760768	0.1499070576			
	5	0.106	0.3	0.25		0.2885003751	0.2404169792			
Avg		0.1035				0.2806422039	0.1917770097			
Worst Case						0.32 (Static, dry)	0.19 (Kinetic, wet)			